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GROWTH PREDICTION AND SITE DETERMINATION IN UNEVEN-AGED TIMBER STANDS [1]

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INTRODUCTION

The prediction of growth in stands of uneven-aged timber has always been a difficult problem in forest measurement. The normal-yield tables that have been developed for nearly every commercial species occurring in even-aged stands have not been adaptable to uneven-aged timber because of too wide variation in the ages of individual trees. For the same reason the evaluation of site in such stands is apt to be unreliable.

For some time growth-prediction methods in use have been based upon the measurement of past diameter growth as revealed by annual rings and the assumption that this growth will be continued at the same rate in the future.[2] These methods are suited only to short-term predictions, and have the further disadvantage that they require an independent estimate of mortality, which is inevitably subject to considerable error.

Permanent sample plots now being established in increasing numbers in all-aged stands will in time yield accurate information on growth. Meanwhile there is a pressing need for a reliable method of growth prediction applicable to the millions of acres of uneven-aged forests now in existence. The northern-hardwood type (sugar maple, yellow birch, hemlock, and associated species) is an important example of these forests, and will be used as an illustration in the method of growth prediction and site determination presented in this paper.

NATURE OF UNEVEN-AGED TIMBER

Undisturbed uneven-aged timber in the Lake States region appears to be composed of an assembly of stands and groups of trees each more or less even-aged. These groups often contain a few scattered individuals considerably older than the rest—remnants of a former stand. Beneath the main body of the stand, in the case of larger timber, may be an understory of newcomers, all considerably younger than the rest. Within each even-aged group, however, the members of the former stand and the younger individuals account for relatively little of the basal area; the majority of trees have evidently originated in a body during the course of a few years.

For example, on the average fifth-acre plot examined in well-stocked stands of mixed hemlock and yellow birch saw timber, the basal area of all trees 1 inch or larger in diameter breast high (d. b. h.)[3] was found to be 38 square feet. Of this, 1 square foot is attributable to the

[1] Received for publication July 23, 1937; issued March, 1938.

[2] CHAPMAN, H. H., and DEMERITT, D. B. ELEMENTS OF FOREST MENSURATION. 452 pp., illus. Albany. 1932. See ch. 24.

[3] 4.5 feet above ground level.

stand of younger individuals and 5 square feet to the former stand, while 84 percent of the total is contributed by the main body of the stand. The trees in this main group range from 6 to 16 inches d. b. h. and from 166 to 182 years. The younger individuals fall entirely in the 2- and 4-inch diameter classes and are all less than 100 years old. The members of the former stand fall in the 16-inch d. b. h. and larger classes and are all older than 200 years. The same type of grouping, occasionally not so pronounced, was found in every stand of northern hardwoods examined for this study.

This division of stands into three age groups is a basic assumption in this method of growth prediction. That it is valid is indicated by several facts: The ages of trees in the younger group almost invariably are arranged about one or two means quite distinct from the average age of the main stand, indicating that these trees have originated in

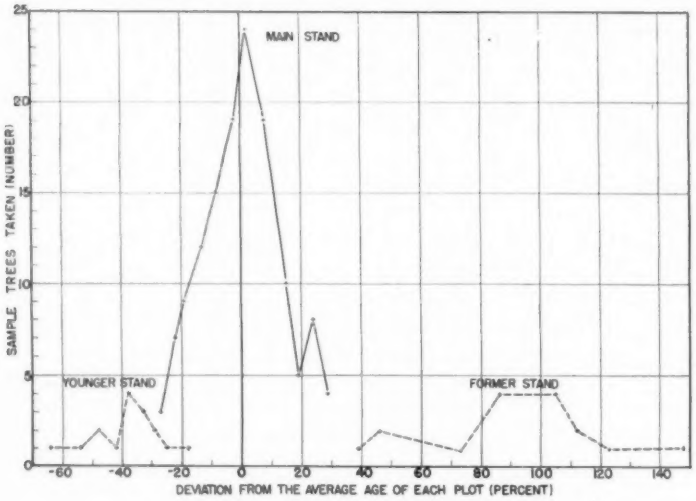

FIGURE 1.—Distribution of sample-tree ages.

groups during periods of a few years, and that these events were definitely subsequent to the establishment of the main stand; the same distinct grouping is found in the members of the former stand. The ages of trees on the average fifth-acre plot, if arranged numerically, appear not to form a continuous series, but to be broken up into groups separated by considerable gaps; furthermore there is almost invariably one group that is decidedly predominant. This condition is illustrated in figure 1, which shows the distribution of ages of 167 sample trees taken on 55 fifth-acre plots in northern-hardwood stands of cordwood size (in which 4-, 6-, and 8-inch trees predominate).

Finally, an examination of stand tables brings out the fact that numbers of main-stand trees by diameter-breast-high classes arrange themselves in a frequency distribution. Members of the younger and former groups show more or less the same tendency, indicating that there are three or more distinct series present. These series, of

course, in an aggregate stand table representing many acres, overlap, and if combined their distribution assumes the typical J-shaped form of uneven-aged stands.

THE FIELD SAMPLE

Circular fifth-acre sample plots were taken throughout Michigan and northern Wisconsin, located mechanically in areas of timber which had not been disturbed by cutting or fire within recent years. Only such undisturbed stands were examined in order that a picture might be obtained of natural developmental trends uninfluenced by either cultural or destructive agencies. The northern-hardwood type was represented by 164 plots. The distribution of these plots by average main-stand diameter classes was as follows:

Average-diameter class, inches	*Plots, Number*	*Average-diameter class, inches*	*Plots, Number*
2	19	14	14
4	40	16	6
6	37	18	0
8	16	20+	3
10	10		
12	19	All	164

On each plot a tally was made of all trees 1 inch or larger in diameter breast high, by species and by the three age groups—younger individuals, main body, and former stand. Judgment of the age group was based upon experience, supplemented by borings for age. Trees were classified "main body" if (1) their ages formed a continuous series about the average; (2) they made up a central group most important from the standpoint of volume; and (3) their ages were set off from those of other trees.

Trees not falling within the limits of this definition were classified as younger individuals or former stand, depending upon their age. Not less than three age-sample trees were taken on each plot, and their species, diameter breast high, age, and age group recorded. Regional volume tables were already available.

ANALYSIS OF THE DATA

MAIN-STAND AGE

In the office the tally on each tally sheet was converted to a per-acre basis; cull trees from this point on were excluded from consideration. The basal area, board-foot volume, and cubic-foot volume per acre represented by the entire tally of sound trees on each sheet were computed. On each sheet were also computed the average stand diameter of the main body, weighted by basal area, and the average age of the main body, as indicated by the age-sample trees. The sheets were then sorted into 2-inch average-diameter classes, and the average age of each class determined. These ages were plotted over their corresponding average diameters, and a smooth curve was drawn through the points (fig. 2, *c*). The resulting values, the average main-

stand ages of northern hardwoods in relation to average main-stand diameters, are as follows:

Average diameter, inches	Average age, years	Average diameter, inches	Average age, years
2	16	14	147
4	28	16	178
6	43	18	209
8	62	20	239
10	86	22	270
12	116	24	301

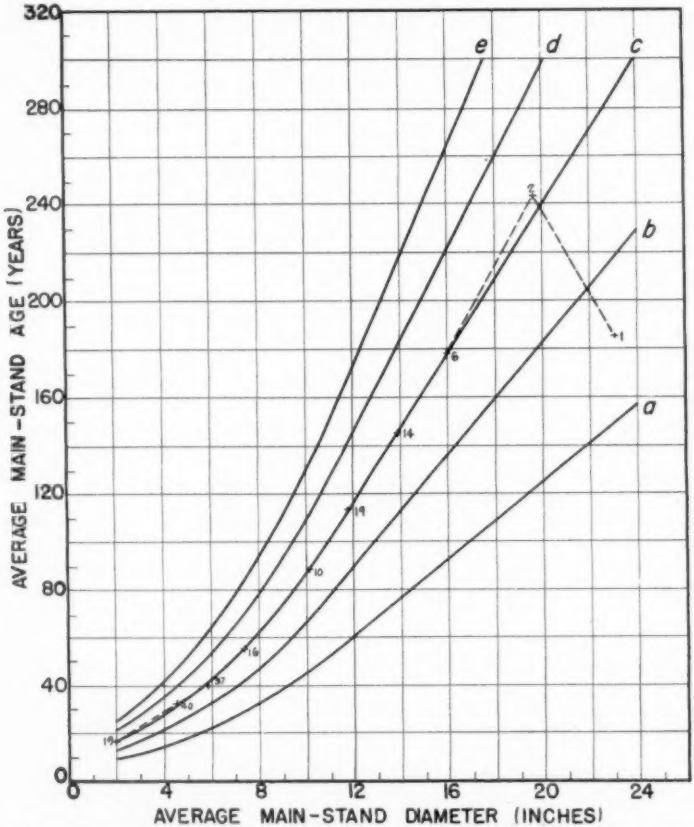

FIGURE 2.—Site-index curves for undisturbed stands of northern hardwoods in Michigan and Wisconsin. In this and subsequent figures 3, 4, 6, 7, and 9 the bases for the plotted points are indicated by numerals.

Such average ages are relative; they express, not the number of years a given stand has been in existence, but the periods of time which that stand has taken to develop from smaller-sized material and the number of years it will require to develop into larger sizes. That is to say, the real significance to be attached to the ages 43 and 116 years for 6-inch and 12-inch stands, respectively, is that it must take about 73 years for stands with a diameter of 6 inches to increase

that diameter to 12 inches. Also, these relative ages are regionwide averages, and are not applicable, therefore, to any specific stands unless those stands happen, by chance, to be average.

BASAL AREA AS AN INDEX OF DENSITY AND YIELD

With these relative ages determined, the next step was to trace the development of stands with increase in the average diameter. Total basal area in square feet per acre was used as a measure of this development. The average basal area per acre was determined for all plots in each average-diameter class, and these basal areas curved over the corresponding average diameters (fig. 3, *b*).

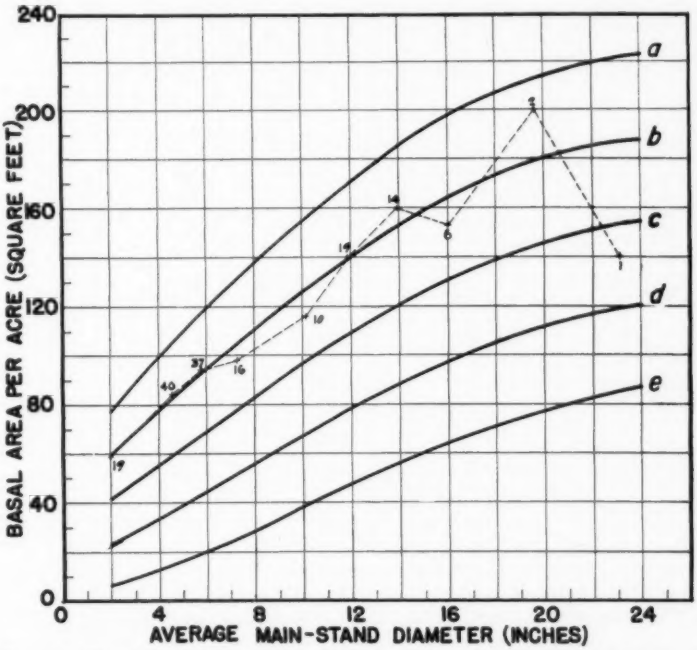

FIGURE 3.—The relation between basal area and average main-stand diameter, five density groups.

This curve represents the way in which basal area increases with the passage of time in an average stand of northern hardwoods, under the fundamental assumption that undisturbed 6-inch stands (for example) will develop during the next 73 years into 12-inch stands essentially similar to the present representatives of the latter diameter class. It is understood, of course, that the field sample gives equal representation to all densities throughout the range of average diameters.

This curve represents the development of stands having an average stocking in basal area, but indicates nothing about the development of well stocked or of poorly stocked stands. The next problem

was to construct curves for the other densities, harmonizing them with the average according to their true relationship to that curve.

In the interpretation of normal-yield tables it is generally assumed that the basal area of an understocked stand will hold a constant percentage relationship to that of the normal stand throughout its development. On the other hand, an allowance is sometimes made for increase in normality—that is, it is sometimes assumed that a young stand with a basal area 50 percent of normal will have a basal area which is 55 or 60 or more percent of normal by the time it reaches maturity. Such an increase in normality would presumably be the result of decreased mortality and increased diameter growth due to an understocked condition.

In order to find the true relationship in this case, the standard deviation in square feet of basal area was calculated for all plots in each diameter class. Since these are standard deviations from different means in the case of each class, they are better expressed as the

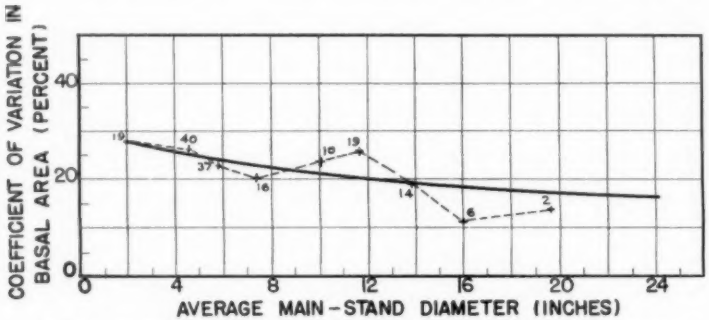

FIGURE 4.—Decrease in coefficient of variation with increasing average main-stand diameter.

coefficient of variation, or the percentage relationship between the standard deviation and its mean. So expressed, they tell a very interesting story.

The average coefficient of variation of northern-hardwood plots belonging to the 2-, 4-, and 6-inch average-diameter classes was found to be 25 percent, meaning that about two-thirds of such plots have basal areas somewhere within the limits of 25 percent more or less than the average. However, plots in the 8-, 10-, and 12-inch diameter classes have a coefficient of variation of 23 percent, and plots with still larger average diameters, only 16 percent. This relationship between the coefficients of variation and their average diameters is expressed in curve form in figure 4.

This appears to mean that the basal area of a poorly stocked stand does not hold a constant percentage relationship to that of the average throughout its development but, on the contrary, gradually approaches the average. It means that the spread of basal areas of individual plots narrows down with increasing average diameter. Poor stocking becomes relatively better, and overstocked stands thin out to some extent. These decreasing coefficients of variation indicate that an increase in normality actually takes place among understocked stands.

These coefficients of variation, then, serve as a basis for constructing more curves of basal area over average diameter above and below the average one already made, in order to express developmental trends in stands of various degrees of stocking (fig. 3). This is done by choosing some convenient arbitrary percentage of the coefficient of variation and using it to fix the interval between successive density curves. In this case, 110 percent of the coefficient of variation was used to determine the position of four new curves of basal area over average diameter, one above and three below the average. This is an adapta-

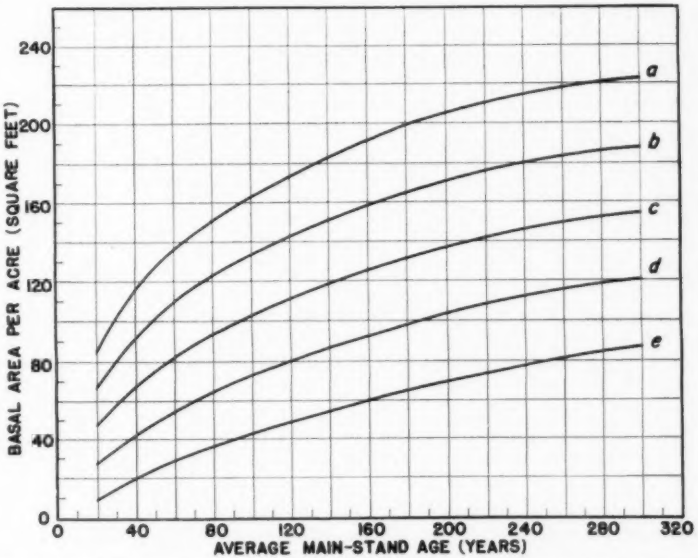

FIGURE 5.—Basal-area growth curves, showing the relationship between basal area and age for five density groups.

tion of the method of constructing harmonized curves described by Osborne and Schumacher.[4]

It is now a simple matter to construct a series of curves of basal area over age (basal-area growth curves). Figure 3 presents the relation of basal area to average diameter; figure 2, c, the relation between age and average diameter for average stands. Figure 5 shows the result of combining these two sets of relationships, thereby eliminating the factor of average diameter common to both.

In table 4 under site index 3, these growth curves are expressed in the form of a growth table. Again, it must be borne in mind that the growth values so far obtained are applicable only to regionwide average stands, and not to any specific stands unless they happen by chance to be average.

The question now arises: Are these basal-area growth values, based as they are upon undisturbed stands, applicable to the general run of

[4] OSBORNE, J. G., and SCHUMACHER, F. X. THE CONSTRUCTION OF NORMAL-YIELD AND STAND TABLES FOR EVEN-AGED TIMBER STANDS. Jour. Agr. Research 51: 547-564, illus. 1935.

stands found throughout a region? The curves for poor density represent what happens to stands that by nature are poorly stocked. Do they also represent what happens to stands poorly stocked as the result of cutting, fire, or some other disturbance?

Growth in basal area is a function of (1) diameter growth and (2) mortality. Unfortunately there are no reliable data available for comparing the mortality in undisturbed stands with that in cut stands. It is possible that mortality rates might be slightly higher in cut stands as a result of disturbance; at any rate, whatever difference exists would probably tend to make growth predictions based on the undisturbed curves slightly liberal when applied to cut stands.

In the case of current growth in diameter a positive check was possible. Increment borings were taken in the field on the undisturbed plots, and borings from cut-over plots taken in other studies were also available. According to these data, half-normal undisturbed stands (considering density 1 as normal) are growing 1.40 times as fast in diameter as normal stands; stands half-normal as the result of cutting are growing nearly 1.45 times as fast. In the case of quarter-normal stands the values are 1.82 and 1.86 for undisturbed and cut stands respectively. Actually these differences are not significant for the size of the sample taken; but they mean, if anything, that the undisturbed-growth curves may be slightly conservative in respect to diameter growth.

It is possible, then, by means of the basal-area growth tables, to predict with some degree of assurance the future basal area and the growth in basal area for different periods of time for any average stand whose age and present basal area per acre are known. It remains only to translate these growth-table values into terms of volume.

This may be done by using the ratio between volume and basal area.

RATIO OF VOLUME TO BASAL AREA

In young stands the ratio of volume—board-foot volume, for example—to basal area is small. This is because few trees have yet reached a size sufficiently large to be given any board-foot volume at all, while there is already considerable basal area. As the stand develops and many trees begin to grow to merchantable size, the board-foot volume increases rapidly. At the same time the basal area is increasing, but at a slower rate, so that the ratio of board-foot volume to square feet of basal area grows rapidly larger. In this way the number of board feet per square foot in a stand increases steadily with age. The increase of the ratio of volume to basal area reflects stand development in terms of the unit of volume employed. It is most rapid at the time when many trees are just coming into merchantability. As time goes on, this effect is less pronounced, and the ratio increase slacks off.

The ratio of volume to basal area also reflects stand composition with regard to the relative numbers of trees of various sizes, an important consideration in dealing with uneven-aged stands. A small ratio indicates the presence in the stand of a large proportion of small trees having considerable basal area but little volume; a large ratio indicates a predominance of large diameters in the stand. Thus increase in ratio during a given period is closely correlated with the

ratio itself at the beginning of the period—that is, future ratio is correlated with present ratio.

For this reason it was not possible to convert the relationship between basal area and age into a relationship between volume and age which might be applied to all stands. A certain volume per acre in one stand may be associated with a high basal area, indicating that many small trees are present and that a large volume growth may be expected; the same volume per acre in another stand of the same age may be associated with a relatively small basal area, indicating that growth possibilities are comparatively limited. Thus in average uneven-aged stands, volume yields are controlled independently by

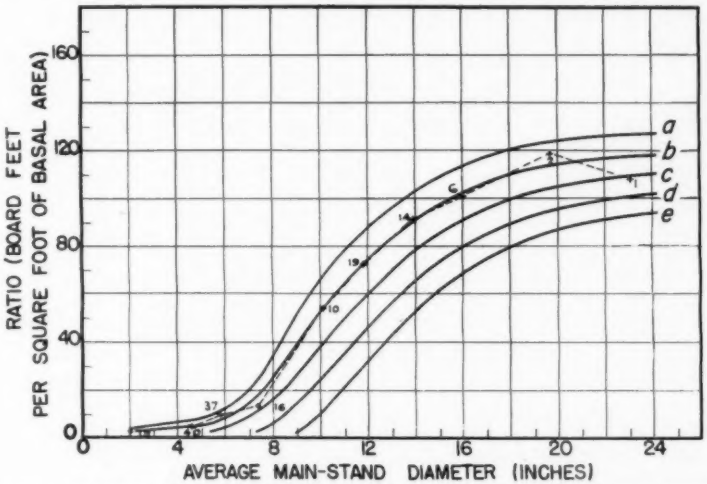

FIGURE 6.—The relationship between the board-foot square-foot ratio and average main-stand diameter, by five ratio groups.

(1) basal area and (2) the ratio of volume to basal area, and some means must be found for constructing ratio growth tables as well as basal-area growth tables.

The same method may be used for constructing such ratio growth tables as was used for making the basal-area tables. The ratio of board-foot volume to basal area, for example, was computed on each tally sheet. This volume, incidentally, is gross Scribner log measure, neither woods cull nor mill cull having been deducted. The ratios so computed were averaged by average-diameter classes, and the averages were used in the construction of a curve showing the relationship between the board-foot square-foot ratio and average diameter (fig. 6, *b*).

The coefficient of variation of the ratios of individual plots within each average-diameter class was then computed, curved (fig. 7), and used to construct additional curves of ratio over average diameter in the same way that the basal-area curves were made.

Finally the relation between age and average diameter (fig. 2, *c*) was used to establish the relationship between ratio and age. (See fig. 8 and table 5.)

Ratio tables for cubic-foot volume were made in the same way (table 6).

The final procedure, then, for predicting the future volume—e. g., board-foot volume at the end of 40 years—of an average stand is as follows: Determine the present board-foot volume and basal area per acre, and from these the present ratio; determine the age of the stand, based on the ages of main-stand trees. From the basal-area growth table find the basal area 40 years hence. From the ratio table find the

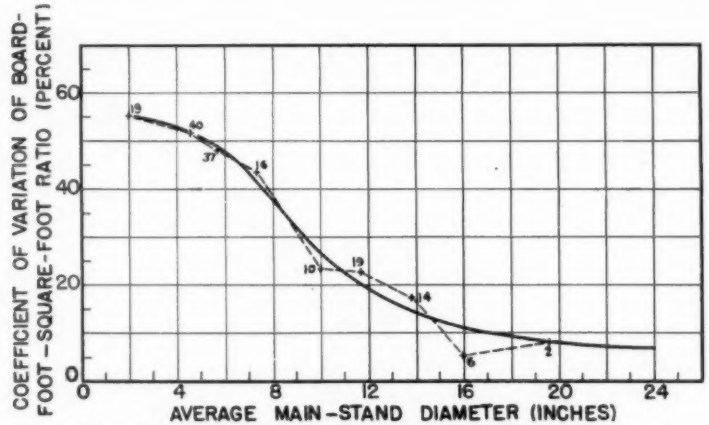

FIGURE 7.—The correlation between coefficient of variation of the board-foot square-foot ratio and average main-stand diameter.

ratio 40 years hence. Multiply the 40-year basal area by the 40-year ratio. The result is the yield in board-foot volume at the end of 40 years.

SITE

One factor—site—remains to be considered. Thus far this method of growth and yield prediction is applicable only to regionwide average stands. How may it be made applicable to individual stands whose sites may differ from the average?

The key to this problem seems to lie with the ages of plots within the various average-diameter classes. The average age of plots in the 8-inch diameter class was found to be 62 years, but the deviation of individual plot ages from this average was considerable. Expressed as the coefficient of variation, it amounted to 29.5 percent of the average. This value of 29.5 percent, moreover, was obtained independently for each of the three average-diameter groups mentioned in the discussion of basal areas, indicating that the standard deviation in age of individual plots holds a constant percentage relationship to its mean, regardless of size.

This is quite a different situation from that found in the case of basal area. With basal area there was a gradual approach toward the average as stands matured; with age there appears to be a factor at work which makes some stands younger, some older than the average for that size; and further than this, as these stands develop, their

variation from the average appears to increase in direct proportion to the length of time involved. In other words, there is a factor which causes some stands to reach a given size much sooner than others, and this factor is cumulative and constant with the passage of time.

Whether this is a single factor or several factors working together, or whether it is termed "site quality" or something else, is not important. For the sake of simplicity it will be so termed here, and defined thus: Site quality is an expression of those natural elements in the habitat which combine to control the rate of increase in the average diameter of a timber stand. According to this definition, if the average site will produce an 8-inch stand in 62 years, then sites producing 8-inch stands in, for example, 32 years should be called good; those requiring 92 years to achieve the same result should be called

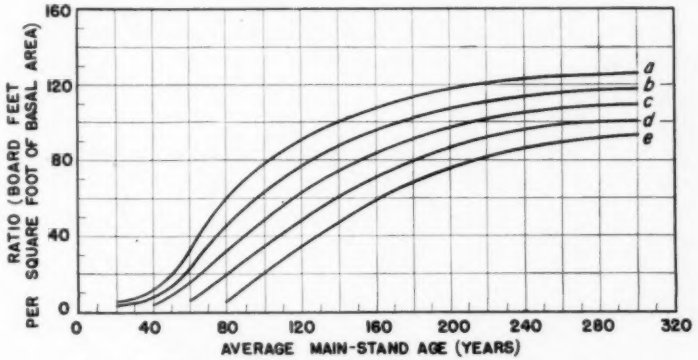

FIGURE 8.—The board-foot square-foot ratio curved over age; five ratio groups.

poor. Furthermore, the range between 32 and 92 may be divided into a series of site classes, from the best to the poorest, and a similar series may be established for each of the average-stand-diameter classes.

This has been done in figure 2, which expresses site quality in terms of average main-stand diameter and average main-stand age for the northern-hardwood type. Site 3, or the average, was represented by the original curve *c* of age over diameter. The other site-index curves were harmonized with the average according to the same method used for basal area and for the board-foot square-foot ratio. The interval employed in this case was 85 percent of the coefficient of variation, giving a convenient spread between site 1 and site 5.

It is, of course, obvious that the definition of site quality expressed in figure 2 is applicable only to stands of northern hardwoods which have not been disturbed by either cultural or destructive agencies. These curves are expressed in tabular form in table 3.

It is now a simple matter to construct basal-area growth curves and ratio-growth curves for sites other than the average. A set of basal-area growth curves for site 1 may be obtained from the curves in figure 5 (representing site 3) by substituting for the site 3 age values the corresponding values read from curve *a* in figure 2. This new age scale would read 10 years at the point now marked 19; 20 years instead of the present 39; 30 years instead of 58; and so forth, indicat-

ing that the same result is achieved in 10 years on site 1 that requires 19 years on site 3, and so on. A set of basal-area and of ratio curves was obtained for each of the five sites, and these curves converted to table form (tables 4, 5, and 6).

STATISTICAL BASIS

The justification for using these data to determine site and predict growth in a stand of northern hardwoods is based upon certain relationships capable of being tested statistically. Such tests were actually carried out, and the following facts established regarding the basic data:

(1) There is no correlation between the density index of plots and their site index. That is, the variation in basal area from the basal-

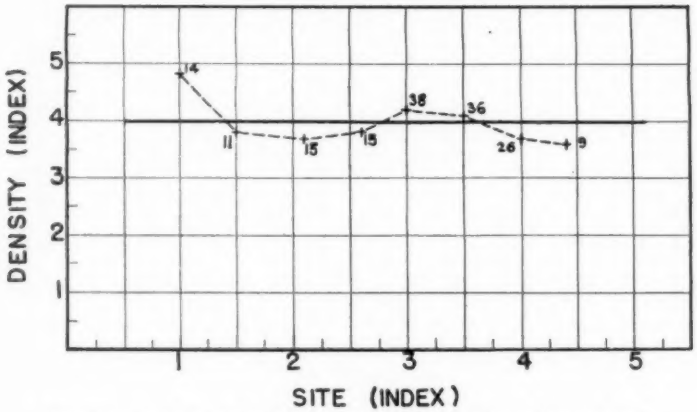

FIGURE 9.—Lack of correlation between the density index of plots and their site index.

area average-diameter curve is not related to age. This, in turn, means that the use of a single basal-area average-diameter curve for all site indices is well justified.

(2) There is good correlation between the age of main-stand sample trees and the average diameter of the plots on which they were taken (correlation coefficient 0.819; 492 cases).

The method of carrying out test No. 1 is illustrated in figure 9. Test No. 2 was carried out by running a partial correlation, using the variables age, average diameter, and density. For this purpose the range of densities represented in figure 3 was further divided to allow for a classification into 21 density groups.

The variation in age of the main stand in the northern-hardwood type depends upon three conditions: (1) The stage of stand development—i. e., whether the stand has a large or small average diameter; (2) site, or variation in place, revealed by the age variation between plot means; and (3) the age variation among individual main-stand sample trees within a plot, determined by the classification of main-stand trees used in the field (pp. 81 to 83). These values are presented in table 1.

TABLE 1.—*Variation in main-stand age, by size classes*

Variation	Mean variance in age by main-stand size class—		
	1	2	3
	Years	*Years*	*Years*
Between plots (V_s^2)	563.68	5,749.25	7,437.98
Between plot means (σ_s^2)	165.48	1,758.61	1,862.64
Within plots (σ_r^2)	67.24	473.42	1,850.06

The mean variance in age increases with the size class of stands. Size-class 1 represents stands with average main-stand diameters of 2 through 6 inches; size-class 2, stands with average diameters of 8 through 12 inches; size-class 3, 14 inches or more.

The variance in age between plots (V_s^2) is made up of two components, namely, variance between plot means (σ_s^2) and variance within plots (σ_r^2). That is to say,

$$V_s^2 = n\sigma_s^2 + \sigma_r^2,$$

where n equals the number of age borings per plot.

The variance between plots is large and is significantly different from the variance within plots, in all stands, as determined by Fisher's Z test.[5] Most of the variance between plot means is due to site differences.

The square of the standard error of the grand mean [6] can be expressed as

$$\sigma_M^2 = \frac{1}{mn}(n\sigma_s^2 + \sigma_r^2), \text{ o}$$

$$\sigma_M^2 = \frac{1}{m}\left(\sigma_s^2 + \frac{\sigma_r^2}{n}\right),$$

where m equals the number of plots taken in each size class, and n equals the number of age borings taken on each plot. In other words, the standard error of the grand mean depends not only upon the two variances (σ_s^2 and σ_r^2), but also upon the number of borings per plot and especially upon the number of plots taken within a given size class.

However, in the case of stands homogeneous in respect to site and average diameter, since σ_s here equals zero, the square of the standard error of the mean age can be expressed in a simpler form—

$$\sigma_M^2 = \frac{\sigma_r^2}{mn}.$$

That is, the standard error here will depend upon the variance within plots and the total number of borings (mn) used.

Table 2 shows how the standard error of age determinations varies with the total number of borings taken, or mn. If, for example, a cruise based on fifth-acre sample plots employs altogether 10 acres of

[5] FISHER, R. A. STATISTICAL METHODS FOR RESEARCH WORKERS. Ed. 6, rev. and enl., 339 pp., illus. Edinburgh [etc.] 1936.

[6] TIPPETT, L. H. C. THE METHODS OF STATISTICS; AN INTRODUCTION MAINLY FOR WORKERS IN THE BIOLOGICAL SCIENCES. 222 pp., illus. London. 1931. See pp. 93 and 176. Tippett's notation has been used throughout this paper.

plots, 50 sample plots in all are taken. If, furthermore, 2 borings are taken on each plot, there will be 100 borings. With this number of borings, the average age of stands of northern hardwoods of size class 2 (growing on all sites) will be estimated with a standard error of 6.3 years, an accuracy adequate for the uses to which the estimated average age is to be put—growth prediction and site determination. Should the stands show no marked differences in site or average diameter, the same 100 borings would estimate the mean age within 2.2 years, on the average.

TABLE 2.—*Standard error of mean-age determinations in relation to size class and number of borings used (all sites combined)*

Plots used (m)	Borings per plot (n)	Total age borings (mn)	Standard error (σ_M) by main-stand size class—			Plots used (m)	Borings per plot (n)	Total age borings (mn)	Standard error (σ_M) by main-stand size class—		
			1	2	3				1	2	3
Number	*Number*	*Number*	*Years*	*Years*	*Years*	*Number*	*Number*	*Number*	*Years*	*Years*	*Years*
10	3	30	4.3	13.8	15.7	50	2	100	2.0	6.3	7.5
10	4	40	4.3	13.7	15.2	50	3	150	1.9	6.2	7.0
10	6	60	4.2	13.6	14.7	50	4	200	1.9	6.1	6.8
20	4	80	3.0	9.7	10.8						

Incidentally, the standard errors of age determination for the northern-hardwood plots used as the basis for this study were as follows: For plots belonging to size-class 1, 1.4 years; size-class 2, 6.5 years; size-class 3, 10.4 years. These standard errors represent about 6 percent of the average ages of the groups of plots involved.

GROWTH TABLES AND THEIR APPLICATION

The method of growth prediction and site determination for uneven-aged timber stands can now be put into practice, using four basic tables, taken from the curves already presented (tables 3, 4, 5, and 6).

TABLE 3.—*Site-index*[1] *table: Basic values for determining site index of a stand whose average diameter and age are known*

[Northern hardwoods—Lake States]

Average main-stand diameter	Base age	Age interval	Average main-stand diameter	Base age	Age interval	Average main-stand diameter	Base age	Age interval
Inches	*Years*	*Years*	*Inches*	*Years*	*Years*	*Inches*	*Years*	*Years*
2.0	4	4	9.5	22	19	17.0	54	46
2.5	5	5	10.0	24	21	17.5	56	48
3.0	6	5	10.5	26	23	18.0	59	50
3.5	7	6	11.0	28	24	18.5	61	52
4.0	8	7	11.5	31	26	19.0	63	54
4.5	9	7	12.0	33	28	19.5	65	56
5.0	10	8	12.5	35	30	20.0	67	57
5.5	11	9	13.0	37	32	20.5	69	59
6.0	12	10	13.5	39	34	21.0	71	61
6.5	13	11	14.0	41	35	21.5	74	63
7.0	14	12	14.5	43	37	22.0	76	65
7.5	16	14	15.0	45	39	22.5	78	67
8.0	17	15	15.5	48	41	23.0	80	68
8.5	18	16	16.0	50	43	23.5	82	70
9.0	20	18	16.5	52	44	24.0	84	72

[1] Site index $= \frac{(\text{average main-stand age}) - (\text{base age})}{(\text{age interval})}$

TABLE 4.—*Growth table: Total stand basal area per acre* [1] *in relation to age, site, and density*

[Northern hardwoods—Lake States]

Main-stand age (years)	Site index 1					Site index 2					Site index 3				
	Density index 1	Density index 2	Density index 3	Density index 4	Density index 5	Density index 1	Density index 2	Density index 3	Density index 4	Density index 5	Density index 1	Density index 2	Density index 3	Density index 4	Density index 5
	Sq. ft.	*Sq. ft.*	*Sq. ft.*	*Sq. ft.*	*Sq. ft.*	*Sq. ft.*	*Sq. ft.*	*Sq. ft.*	*Sq. ft.*	*Sq. ft.*	*Sq. ft.*	*Sq. ft.*	*Sq. ft.*	*Sq. ft.*	*Sq. ft.*
20	114.2	90.1	66.0	42.0	17.9	95.4	74.3	53.2	32.1	11.0	83.5	64.8	46.0	27.2	8.5
40	146.8	118.7	90.6	62.4	34.3	128.6	102.6	76.6	50.7	24.7	115.2	91.2	67.2	43.1	19.1
60	170.3	139.6	109.6	78.4	47.7	149.4	120.9	92.4	63.8	35.3	135.7	108.8	81.9	55.0	28.1
80	188.8	156.3	123.8	91.3	58.8	165.0	134.8	104.5	74.2	44.0	149.9	121.4	92.8	64.3	35.8
100	203.1	169.4	135.6	101.8	68.1	178.2	146.6	115.0	83.5	51.9	162.0	132.1	102.2	72.4	42.5
120	212.3	178.2	144.1	110.0	75.9	189.7	157.0	124.2	91.5	58.8	172.9	141.8	110.8	79.7	48.6
140	219.1	184.9	150.6	116.4	82.2	199.4	165.8	132.3	98.8	65.2	182.6	150.5	118.4	86.4	54.3
160	222.9	188.9	154.9	120.9	86.9	207.3	173.2	139.0	104.9	70.8	191.4	158.4	125.4	92.5	59.5
180						213.4	179.1	144.8	110.4	76.1	198.7	165.1	131.6	98.0	64.4
200						218.1	183.8	149.4	115.1	80.8	204.8	170.9	137.0	103.1	69.2
220						221.4	187.4	153.4	119.3	85.3	209.8	175.8	141.7	107.6	73.6
240											214.1	179.9	145.8	111.6	77.4
260											217.5	183.3	149.1	114.9	80.7
280											220.3	186.2	152.2	118.1	84.0
300											222.6	188.7	154.8	121.0	87.1

Main-stand age (years)	Site index 4					Site index 5				
	Density index 1	Density index 2	Density index 3	Density index 4	Density index 5	Density index 1	Density index 2	Density index 3	Density index 4	Density index 5
	Sq. ft.	*Sq. ft.*	*Sq. ft.*	*Sq. ft.*	*Sq. ft.*	*Sq. ft.*	*Sq. ft.*	*Sq. ft.*	*Sq. ft.*	*Sq. ft*
20	75.8	58.4	41.0	23.6	6.2	70.0	53.5	37.0	20.4	3.9
40	104.6	82.1	59.6	37.1	14.6	97.4	76.0	54.6	33.2	11.8
60	124.8	99.2	73.6	47.9	22.3	115.7	91.4	67.2	43.0	18.7
80	139.3	111.8	84.4	57.0	29.5	129.7	103.5	77.3	51.1	24.9
100	150.6	122.0	93.3	64.6	36.0	140.7	113.2	85.7	58.2	30.7
120	160.2	130.6	100.9	71.2	41.6	150.2	121.6	93.1	64.6	36.0
140	169.2	138.6	107.9	77.2	46.6	158.6	129.2	99.7	70.2	40.8
160	177.7	146.1	114.5	82.9	51.3	166.2	136.0	105.7	75.4	45.2
180	185.3	153.0	120.6	88.2	55.9	173.3	142.2	111.2	80.1	49.0
200	191.9	158.9	126.0	93.0	60.0	179.9	148.1	116.2	84.4	52.6
220	197.9	164.4	131.0	97.5	64.0	186.2	153.7	121.2	88.6	56.1
240	203.0	169.2	135.4	101.5	67.7	192.1	159.0	125.8	92.6	59.5
260	207.3	173.2	139.2	105.1	71.0	197.4	163.8	130.2	96.5	62.9
280	210.9	176.7	142.5	108.3	74.1	202.1	168.2	134.2	100.2	66.3
300	214.1	179.8	145.6	111.3	77.0	206.4	172.2	138.0	103.8	69.6

[1] Trees 1 inch and more in diameter breast high; cull trees excluded.

Take as an example a 100-acre stand of northern hardwoods in eastern Wisconsin. A 10-percent inventory cruise is to be run, using fifth-acre plots. A prediction is required of the annual growth in board feet for the next 20 years.

An accuracy of age determination representing a standard error of about 6 years is desired. A cursory inspection shows that the timber all falls in size-class 2; table 2 shows that little increased accuracy is to be obtained from numerous borings on each plot, about two borings per plot probably being adequate. The cruise is run, the data com-

piled in the office, and the following figures obtained (excluding cull trees):

(1) Average volume per acre: 8,250 board feet (Scribner).
(2) Average basal area per acre: 150.0 square feet.
(3) Board-foot square-foot ratio: 55.0.
(4) Average main-stand diameter: 9.2 inches.
(5) Average main-stand age: 42 years.

Table 3 indicates that site index is $\frac{42-21}{18}$, or 1.2, called 1 (excellent).

Table 4, site index 1, 42 years, places 150.0 square feet nearest density index 1 (fully stocked). The increase in basal area during the next 20 years (from age 42 to age 62) for density index 1, site 1, is, by simple interpolation,

$$\left[\frac{18}{20}(170.3-146.8)\right]+\left[\frac{2}{20}(188.8-170.3)\right],$$

or 23.0 square feet. The basal area to be expected 20 years hence is then 150.0+23.0=173.0 square feet per acre.

TABLE 5.—*Growth table: ratio (board feet per square foot of basal area)*[1] *in relation to age, site, and ratio group*

[Northern hardwoods—Lake States]

Main-stand age (years)	Site index 1					Site index 2					Site index 3				
	Ratio group *a*	Ratio group *b*	Ratio group *c*	Ratio group *d*	Ratio group *e*	Ratio group *a*	Ratio group *b*	Ratio group *c*	Ratio group *d*	Ratio group *e*	Ratio group *a*	Ratio group *b*	Ratio group *c*	Ratio group *d*	Ratio group *e*
20	9.6	6.2	2.8			5.8	3.7				4.5	2.8			
40	55.6	42.5	29.4	16.3	3.2	21.0	14.8	8.5	2.3		9.6	6.2	2.9		
60	88.2	74.0	59.8	45.6	31.4	58.3	44.8	31.4	17.9	4.4	31.8	23.0	14.1	5.3	
80	106.2	93.6	81.1	68.6	56.0	80.8	66.5	52.2	37.8	23.5	58.6	45.3	32.0	18.7	5.4
100	116.8	106.0	95.3	84.6	73.8	96.7	83.0	69.4	55.8	42.1	77.5	63.0	48.6	34.2	19.7
120	122.8	113.4	104.1	94.8	85.4	107.7	95.2	82.6	70.1	57.6	90.5	76.5	62.4	48.4	34.4
140	126.0	117.4	108.8	100.2	91.6	115.4	104.1	92.8	81.5	70.2	100.4	87.2	74.0	60.8	47.6
160	127.1	118.8	110.4	102.1	93.8	120.3	110.2	100.1	90.0	79.9	108.2	95.9	83.6	71.4	59.1
180						123.6	114.4	105.2	95.9	86.7	113.9	102.6	91.4	80.2	68.9
200						125.7	117.0	108.3	99.6	90.9	118.2	107.8	97.4	87.0	76.6
220						126.7	118.4	110.0	101.6	93.3	121.4	111.7	102.0	92.3	82.6
240											123.9	114.8	105.6	96.5	87.4
260											125.5	116.8	108.0	99.2	90.5
280											126.6	118.1	109.6	101.1	92.6
300											127.1	118.8	110.4	102.1	93.8

Main-stand age (years)	Site index 4					Site index 5				
	Ratio group *a*	Ratio group *b*	Ratio group *c*	Ratio group *d*	Ratio group *e*	Ratio group *a*	Ratio group *b*	Ratio group *c*	Ratio group *d*	Ratio group *e*
20	4.0	2.6				3.8	2.4			
40	7.0	4.3				5.8	3.8			
60	16.0	11.2	6.3			10.0	6.6	3.1		
80	38.1	27.8	17.6	7.3		22.2	15.6	9.1	2.5	
100	59.8	46.3	32.8	19.3	5.8	42.0	31.0	19.9	8.9	
120	74.5	60.0	45.4	30.9	16.4	59.9	46.3	32.8	19.2	5.6
140	86.2	71.8	57.4	42.9	28.5	72.8	58.4	44.1	29.8	15.4
160	95.2	81.5	67.8	54.0	40.3	83.0	68.6	54.2	39.9	25.5
180	102.7	89.8	76.8	63.8	50.9	91.6	77.5	63.4	49.4	35.3
200	108.9	96.7	84.6	72.4	60.2	98.6	85.1	71.6	58.1	44.6
220	113.8	102.3	90.8	79.4	67.9	104.4	91.5	78.6	65.7	52.8
240	117.2	106.4	95.7	85.0	74.2	109.2	97.0	84.8	72.6	60.4
260	119.9	109.8	99.6	89.5	79.4	113.1	101.5	90.0	78.4	66.8
280	122.1	112.6	103.0	93.5	84.0	116.3	105.4	94.4	83.4	72.5
300	124.0	115.0	106.0	96.9	87.9	118.7	108.4	98.2	87.9	77.6

[1] Scribner scale, gross. Trees 9 inches and more d. b. h., to a variable top diameter, the minimum being 8 inches inside bark (6 inches for conifers); cull trees excluded.

TABLE 6.—*Growth table: Ratio (cubic feet per square foot of basal area)* [1] *in relation to age, site, and ratio group*

[Northern hardwoods—Lake States]

Main-stand age (years)	Site index 1					Site index 2					Site index 3				
	Ratio group *a*	Ratio group *b*	Ratio group *c*	Ratio group *d*	Ratio group *e*	Ratio group *a*	Ratio group *b*	Ratio group *c*	Ratio group *d*	Ratio group *e*	Ratio group *a*	Ratio group *b*	Ratio group *c*	Ratio group *d*	Ratio group *e*
20	13.4	10.3	7.2	4.2	1.1	9.5	7.1	4.8	2.4	----	7.7	5.7	3.8	1.8	----
40	22.8	18.7	14.6	10.6	6.5	17.4	13.7	10.0	6.4	2.7	13.5	10.4	7.3	4.2	1.1
60	26.8	23.0	19.2	15.3	11.5	23.2	19.1	15.0	10.9	6.8	19.4	15.5	11.6	7.7	3.8
80	28.7	25.3	21.8	18.4	15.0	26.0	22.0	18.1	14.2	10.2	23.3	19.2	15.2	11.1	7.0
100	29.7	26.6	23.5	20.4	17.3	27.7	24.0	20.4	16.7	13.0	25.6	21.6	17.6	13.7	9.7
120	30.2	27.3	24.4	21.6	18.7	28.7	25.3	22.0	18.6	15.2	27.0	23.2	19.4	15.7	11.9
140	30.5	27.8	25.0	22.2	19.5	29.5	26.4	23.2	20.0	16.9	28.0	24.4	20.8	17.3	13.7
160	30.7	28.0	25.4	22.7	20.0	30.0	27.0	24.0	21.1	18.1	28.8	25.4	22.0	18.7	15.3
180	----	----	----	----	----	30.3	27.4	24.6	21.8	18.9	29.4	26.2	23.0	19.8	16.6
200	----	----	----	----	----	30.5	27.7	25.0	22.2	19.4	29.8	26.8	23.7	20.6	17.6
220	----	----	----	----	----	30.6	27.9	25.2	22.5	19.8	30.1	27.2	24.2	21.3	18.4
240	----	----	----	----	----	----	----	----	----	----	30.3	27.5	24.6	21.8	19.0
260	----	----	----	----	----	----	----	----	----	----	30.5	27.7	25.0	22.2	19.4
280	----	----	----	----	----	----	----	----	----	----	30.6	27.9	25.2	22.4	19.7
300	----	----	----	----	----	----	----	----	----	----	30.7	28.0	25.3	22.6	19.9

Main-stand age (years)	Site index 4					Site index 5				
	Ratio group *a*	Ratio group *b*	Ratio group *c*	Ratio group *d*	Ratio group *e*	Ratio group *a*	Ratio group *b*	Ratio group *c*	Ratio group *d*	Ratio group *e*
20	6.5	4.8	3.1	1.4	----	5.8	4.3	2.7	1.2	----
40	11.3	8.6	5.9	3.2	----	9.6	7.2	4.9	2.5	----
60	16.2	12.7	9.2	5.7	2.2	13.7	10.6	7.4	4.3	1.2
80	20.4	16.4	12.4	8.5	4.5	17.7	14.0	10.2	6.5	2.8
100	23.4	19.3	15.2	11.1	7.0	21.1	17.0	13.0	9.0	4.9
120	25.2	21.2	17.2	13.2	9.2	23.4	19.3	15.2	11.1	7.0
140	26.5	22.6	18.8	15.0	11.1	25.0	21.0	17.0	12.9	8.9
160	27.5	23.8	20.2	16.5	12.8	26.2	22.3	18.4	14.5	10.6
180	28.3	24.8	21.3	17.8	14.3	27.1	23.4	19.6	15.8	12.1
200	28.9	25.6	22.2	18.8	15.5	27.8	24.2	20.6	17.0	13.4
220	29.3	26.1	22.9	19.7	16.5	28.4	24.9	21.4	18.0	14.5
240	29.7	26.6	23.5	20.4	17.3	28.9	25.6	22.2	18.8	15.5
260	29.9	26.9	24.0	21.0	18.0	29.3	26.1	22.8	19.6	16.4
280	30.1	27.2	24.3	21.4	18.5	29.6	26.5	23.4	20.2	17.1
300	30.3	27.5	24.6	21.8	19.0	29.8	26.8	23.8	20.7	17.7

[1] Trees 5 inches and more in d. b. h., to a 4-inch top inside bark; cull trees excluded.

Table 5, site index 1, 42 years, places the ratio of 55.0 in ratio group *a* (highest). Twenty-year ratio increase in this group is, by interpolation, 31.1, making the board-foot square-foot ratio 20 years hence 55.0+31.1, or 86.1.

Volume per acre in board feet 20 years hence is thus 173.0×86.1, or 14,895 board feet; and growth per acre for the period, 14,895—8,250, or 6,645 board feet. This means that a growth of 332 board feet per acre per year (including woods and mill cull) may be expected for the next 20 years.

In this example it was assumed that the stand belong entirely to a single size class. Where different sizes are represented on an area, a separate growth estimate should properly be made for each.

Take as a second example a stand in the eastern Upper Peninsula of Michigan, similar to the first in area and in cruise requirements. In this case, however, the timber falls in size class 3, and reference to table 2 shows that at least 200 borings are required, or 4 borings per plot. A cruise is run, and these data obtained:

(1) Average volume per acre: 10,232 board feet (Scribner).
(2) Average basal area per acre: 95.0 square feet.
(3) Board-foot square-foot ratio: 107.7.
(4) Average main-stand diameter: 17.0 inches.
(5) Average main-stand age: 276 years.

Table 3 puts this stand in site index 5, or poor. Table 4, site index 5, 276 years, puts 95.0 square feet in density index 4 (poorly stocked). Basal-area increase from 276 to 296 years is, by interpolation, 3.6 square feet, making basal area 20 years hence 98.6 square feet.

Table 5, site index 5, 276 years, indicates that a ratio of 107.7 falls in group *b*. Ratio increase in this group from 276 to 296 years is 3.2, meaning that the board-foot square-foot ratio to be expected 20 years hence is 110.9.

Volume per acre 20 years hence is 98.6×110.9, or 10,935 board feet Scribner. Growth for the 20-year period is 703 board feet, and growth per acre per year 35 board feet gross Scribner.

These two examples make it apparent that volume growth is controlled chiefly by the four factors: Site, age, density, and the proportion of small trees just ready to enter merchantability. The last factor is reflected in the ratio of volume to basal area.

SUMMARY

A method is presented for determining site and predicting growth in uneven-aged timber. Taking advantage of the fact that a main even-aged group of trees may be distinguished within each uneven-aged stand, the basal areas of stands are curved over the ages of these main groups, and these curves are used in conjunction with the ratio of volume to basal area in predicting future yields and growth. Site is introduced as a function of age and average diameter. This series of relationships may be expressed in the form of site and growth tables, which can then be applied to any stand of the cover type in question.

A statistical analysis of the field data obtained in the northern-hardwood cover type shows that (1) use of the three correlations—basal area with average diameter, volume basal-area ratio with average diameter, and age with average diameter—as a basis for growth prediction, is well justified; (2) significant, even-aged groups of trees are actually present in so-called "uneven-aged" stands; (3) only a small error is involved in determining the average age of these groups, this error depending upon the number of sample plots taken, and to some extent upon the number of age-sample trees bored on each plot.

RELATION OF CERTAIN PLANT CHARACTERS TO STRENGTH OF STRAW AND LODGING IN WINTER WHEAT [1]

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INTRODUCTION

Lodging of wheat is often an important factor influencing the final yield of grain in the more humid sections of the country. Hence the development of varieties resistant to lodging is an important objective in most breeding programs. However, lodging under field conditions usually occurs so irregularly that an accurate evaluation of the tendency of new strains and varieties to lodge is difficult to obtain. Because of this, numerous efforts have been made to find a satisfactory method of testing new strains with respect to this characteristic. Ordinarily, these have consisted of mechanical devices designed to measure resistance of the culm either to bending or to breaking. Other studies have been concerned with plant characters which, it seems, might be associated with resistance to lodging.

REVIEW OF LITERATURE

The literature on lodging is rather extensive and extends at least as far back as 1789, when Sir Humphrey Davy (*4*)[3] associated lodging of cereals with low silica content of the straw. Comprehensive reviews of early literature have been given by Welton and Morris (*13*), the Imperial Bureau of Plant Genetics, School of Agriculture,[4] Phillips, Davidson, and Weihe (*8*), and others. The reader is referred to these publications for results of research prior to 1931.

Brady (*1*) recently made extensive studies of external and internal characters of three oat varieties in an attempt to find some morphological or anatomical character associated with lodging. He found that thickness of the culm wall, number of vascular bundles, width of lignified tissue, and width of sclerenchyma were all closely associated with varietal differences in lodging, but that external characters such as height of plant and length and diameter of lower internodes were equally good indexes. He concluded that all characters were so subject to soil variation that their use for the isolation of strains resistant to lodging could be used only on a relative basis. Clark and Wilson (*2*) studied the relationship of lodging, tillering, and

[1] Received for publication Apr. 13, 1937; issued March 1938. A report of cooperative investigations at Texas Substation No. 6, Denton, Tex., conducted by the Division of Cereal Crops and Diseases, Bureau of Plant Industry, and the Texas Agricultural Experiment Station. Submitted as a thesis in partial fulfillment of the requirements for the master of science degree at the Kansas State College of Agriculture and Applied Science, Feb. 1, 1936.

[2] The author expresses his appreciation to Dr. H. H. Laude, Department of Agronomy, Kansas State College of Agriculture and Applied Science; to Dr. K. S. Quisenberry, Division of Cereal Crops and Diseases, Bureau of Plant Industry, U. S. Department of Agriculture; and to Dr. P. C. Mangelsdorf and P. B. Dunkle, of the Texas Agricultural Experiment Station, for helpful suggestions in carrying out the experiment and preparing the manuscript.

[3] Reference is made by number (italic) to Literature Cited, p. 119.

[4] IMPERIAL BUREAU OF PLANT GENETICS, SCHOOL OF AGRICULTURE. LODGING IN CEREALS—A REPORT OF RESEARCH. 8 pp. 1931. [Mimeographed.]

breaking strength of straw in varieties of spring wheat and barley. They found significant differences in breaking strength between varieties but no correlation between breaking strength and lodging in the field. A significant correlation between diameter of culm and breaking strength was found. Hall (*6*), in a study of lodging in corn, found lodging significantly correlated with the force necessary to pull the plant from the soil, but little or no relationship between the amount of lodging and ear height, length of underground stem (mesocotyl), stalk cross section, amount of disease of the stalk, size of brace roots, number of suckers, or weight of ears.

Smith (*12*) studied breaking strength of F_2 and F_3 strains from a cross of Gopher × Rainbow oats. He concludes that the use of the breaking strength of straw test as a means of distinguishing plants superior in this respect is not justified. Ramiah and Dharmalingam (*9*) found only a single-factor difference between strong- and weak-strawed varieties of rice.

Salmon (*10*) devised an instrument for measuring the strength of straw of small grains and he presented data to show that this measurement was correlated with lodging behavior in the field. This instrument has also been used by Salmon and Laude (*11*, *pp. 57–58*), Davis and Stanton (*3*), and Leidigh, Mangelsdorf, and Dunkle (*7*), and their data support Salmon's conclusions.

MATERIAL AND METHODS

The data obtained in this study were secured during the crop seasons of the 4-year period 1931–34 from plants of various wheat varieties grown at Texas Substation No. 6, Denton, in north-central Texas. The number of varieties varied from a minimum of 18 in 1931 to a maximum of 129 in 1934. Prior to 1934 the material for testing was obtained from the guard rows of the replicated wheat nursery plots. In 1934, a special seeding was made in single three-row, 8-foot plots. Plants for the study were taken from the center row of each plot. The rate of seeding was uniformly 8 grams per row.

Various characters were studied, including the breaking strength of straw, height of plants, length of lower internode, diameter and weight per unit length of culm, date of maturity, weight of grain from 100 heads, weight of 100 culms, and stand.

Determinations on strength of straw were made with the machine devised by Salmon and referred to above. Plants for testing were pulled or cut at the surface of the ground and cured under cover before tests and measurements were taken. Twenty determinations of 5 straws each, or a total of 100 straws, were made for each variety. The data are reported as the average number of pounds required to break five straws. Tests were made in all instances on the first upright internode above the crown of the plant.

Diameter of culm, length of culm, weight per unit length of culm, and length of the lower internode are based on 100 determinations for each variety. Each individual determination of weight per unit length of culm consisted of the weight of a 10-cm section, including the one node, between the internode used for the strength-of-straw determinations and the one immediately above. Plant height was measured in the field in 1932 and included the height of the entire plant. In 1933 and 1934 the length of the culm after the head was removed was determined. Whenever lodging occurred a record was

made consisting of estimates of the percentage of the plants permanently lodged.

Statistical treatment of the data has been confined to measures of the variability of breaking strength and the calculation of coefficients of correlation. The data on strength of straw were analyzed by the analysis of variance method as developed by Fisher (*5*). Simple correlation coefficients were determined for all possible combinations among the characters studied. Partial correlation coefficients were determined in a few instances where it seemed they might be of value. Many of the varieties are susceptible to rust, and in 1934, when it appeared that rust would probably interfere with the principal objective of the experiment, the entire planting was dusted with sulphur at frequent intervals, and rust did not develop in damaging amounts at least until late in the season. The breaking strength of the straw of rusted and nonrusted culms of certain varieties was determined, and no significant differences were observed. This, together with general observations, indicates that for the purposes of this study rust probably did not materially influence the results.

A considerable number of the varieties grown at Denton have been grown also at other experiment stations in the United States at which lodging has occurred. Data on lodging supplied by the various stations have been studied in relation to the breaking strength of the straw as determined at Denton, and the results are reported herein.

EXPERIMENTAL RESULTS

The data on strength of straw, measurements of certain morphological characters, and records of stand, date of maturity, lodging, and rust for the various varieties grown at the Denton substation in 1932, 1933, and 1934 are given in tables 1, 2, and 3. In each table the varieties are listed in the order of breaking strength of straw. Determinations of breaking strength of straw were also made in 1931, but no other data were recorded. The analysis of variance for the breaking strength of the straw is given in table 4, and the correlation coefficients for various pairs of characters are given in table 5.

TABLE 1.—*Breaking strength of straw and various agronomic characters of 65 wheat varieties and strains grown at Texas Substation No. 6, Denton, Tex., 1932*

Variety or strain	T. S. No.[1]	C. I. No.[2]	Date of first heading	Rust		Plant height	Length of lower internode	Diameter of culm	Estimated lodging	Weight required to break 5 culms
				Leaf	Stem					
				Pct.	*Pct.*	*Cm*	*Cm*	*Mm*	*Pct.*	*Lb.*
Clarkan	20400	8858	Apr. 28	45	40	107	8.78	3.03	T[3]	6.06
Harvest Queen	15837	6199	Apr. 29	83	35	108	9.16	2.95	1	5.89
Ohio, T. N. 1047	18567	.....	do.....	71	50	104	7.76	2.87	1	5.80
Kawvale	12577	8180	Apr. 27	21	18	99	8.05	2.85	1	5.25
P1066×Burbank	20425	10087	Apr. 25	63	18	97	6.80	2.66	9	5.23
Mediterranean selection	5933-36	.....	Apr. 24	13	24	107	10.00	2.87	24	5.17
Fultz	20474	3416	Apr. 22	79	9	91	7.25	2.83	4	5.08
Mediterranean selection	5933-32	.....	Apr. 23	26	35	102	9.03	2.63	34	4.92
Do	5933-7	.....	do.....	21	18	102	9.86	2.71	38	4.91

[1] Accession number of Texas Agricultural Experiment Station.
[2] C. I. refers to accession number of the Division of Cereal Crops and Diseases, formerly Office of Cereal Investigations.
[3] T=trace.

TABLE 1.—*Breaking strength of straw and various agronomic characters of 65 wheat varieties and strains grown at Texas Substation No. 6, Denton, Tex., 1932*—Con.

Variety or strain	T. S. No.	C. I. No.	Date of first heading	Rust		Plant height	Length of lower internode	Diameter of culm	Estimated lodging	Weight required to break 5 culms
				Leaf	Stem					
				Pct.	*Pct.*	*Cm*	*Cm*	*Mm*	*Pct.*	*Lb.*
Fultzo-Mediterranean selection	20429	------	Apr. 27	75	8	99	8.21	2.82	3	4.84
Fulcaster	7082	6471	Apr. 29	78	43	107	8.40	2.62	8	4.81
Sutton	15832	10053	May 1	24	50	102	8.25	2.54	13	4.80
Smithsonian	20431	10022	May 2	20	30	104	7.07	2.57	64	4.79
Sibley No. 81	20427	10084	Apr. 27	45	10	99	7.95	2.52	18	4.76
Early Blackhull	15838	8856	Apr. 20	83	T	89	8.63	2.59	2	4.71
Denton (average of 6 check plots)	9236	8265	Apr. 27	15	24	102	8.42	2.53	9	4.70
Kanred×Fulcaster selection	20401	------	Apr. 26	26	15	102	9.05	2.76	3	4.69
Mediterranean selection	5933–35	------	Apr. 23	11	21	108	9.68	2.68	36	4.64
Kanred×Marquis	20426	11374	Apr. 24	36	3	89	7.58	2.51	8	4.46
Quivira	15833	8886	Apr. 23	30	5	94	7.54	2.44	9	4.45
Mediterranean selection	5933–23	11525	Apr. 25	4	16	107	8.19	2.67	10	4.44
Do	5933–38	------	Apr. 23	13	25	107	10.30	2.70	30	4.37
Do	9015–105–1	11587	Apr. 27	14	40	104	9.11	2.61	21	4.36
White Mediterranean	15834	10023	Apr. 23	68	41	102	9.26	2.47	10	4.36
Kanred×Marquis	20390	10090	Apr. 29	13	14	99	10.17	2.65	29	4.34
Minturki	20483	6155	May 1	82	10	107	7.75	2.45	2	4.30
Mediterranean selection	3015–63	------	Apr. 26	6	23	99	9.57	2.50	9	4.20
Kanred×Marquis, Kansas 2640	20391	------	Apr. 27	23	9	97	9.37	2.56	4	4.14
Kanred×Fulcaster selection	23049	------	do	31	23	104	9.33	2.56	21	4.12
Mediterranean selection	3015–130	------	Apr. 26	21	24	102	8.71	2.44	9	4.07
Blackhull	7172	6251	Apr. 29	80	8	99	8.73	2.38	20	4.06
Kanred×Fulcaster	20402	------	Apr. 28	18	13	104	9.39	2.63	8	4.05
Beloglina selection	20424	8884	May 2	74	13	97	7.38	2.37	35	4.03
Kanred×Hard Federation	20418	10092	Apr. 22	48	10	86	7.77	2.50	4	4.02
Turkey selection	20376	10100	Apr. 30	88	26	91	7.39	2.34	50	4.02
Tenmarq	12578	6936	Apr. 29	44	9	99	8.13	2.48	11	3.93
Mediterranean selection	5933–20	10085	Apr. 24	15	11	99	9.13	2.30	13	3.92
Do	5933–34	11526	do	24	11	99	9.68	2.32	9	3.90
Red May selection	7250–1	------	Apr. 27	30	25	89	8.94	2.44	9	3.90
Mediterranean selection	3015–81	10086	Apr. 26	33	16	97	7.82	2.29	33	3.90
Kanred selection	20415	10099	May 1	76	10	99	8.89	2.48	28	3.90
Cheyenne	18566	8885	do	78	10	94	8.14	2.51	6	3.87
Oro	23389	8220	do	75	8	99	8.81	2.53	6	3.85
Kanred×Hard Federation	20416	11373	Apr. 21	51	8	86	7.68	2.47	4	3.79
Tenmarq selection	20421	10089	Apr. 29	35	8	99	8.58	2.56	11	3.77
Turkey selection	20370	10094	May 1	96	8	89	7.24	2.26	4	3.70
Nebraska No. 60	15835	6250	do	88	14	97	8.00	2.36	19	3.66
Kharkof	16830	1442	do	81	11	97	7.12	2.26	10	3.64
Mediterranean selection	3015–72	11567	Apr. 27	48	23	99	8.82	2.29	39	3.59
Kanred×Hard Federation	20419	10093	Apr. 19	46	6	84	7.78	2.39	0	3.58
Fulhard	20420	8257	Apr. 26	80	11	97	9.43	2.35	5	3.54
Turkey selection	20375	10098	Apr. 28	94	9	91	7.84	2.23	4	3.53
Kanred×Hard Federation	20417	10091	Apr. 19	38	4	84	8.35	2.47	0	3.51
Nebraska No. 28	15836	5147	Apr. 15	85	0	74	8.37	2.31	0	3.50
Turkey selection	20371	10095	Apr. 30	94	10	86	7.20	2.23	6	3.49
Do	20368	10083	Apr. 29	75	8	97	8.32	2.27	39	3.48
Minturki×Beloglina-Buffum	20422	10088	May 2	81	9	102	8.43	2.26	24	3.48
Kanred×Minturki	20423	10012	do	75	9	99	7.61	2.23	29	3.45
Canadian hybrid	20428	------	Apr. 20	88	10	91	8.17	2.27	13	3.42
Kanred	11763	5146	May 1	76	8	91	9.59	2.35	35	3.40
Turkey selection	20373	10097	Apr. 29	94	8	89	6.41	2.09	10	3.39
Do	20374	10016	Apr. 28	96	9	91	7.97	2.19	4	3.39
Do	20377	11375	Apr. 29	91	16	94	7.83	2.17	15	3.36
Do	20372	10096	do	96	9	89	6.85	2.17	4	3.30
Do	20369	10015	Apr. 30	94	6	91	6.50	2.15	6	3.26

TABLE 2.—*Breaking strength of straw and various agronomic characters of 44 wheat varieties and strains grown at Texas Substation No. 6, Denton, Tex., 1933*

Variety or strain	T. S. No.	C. I. No.	Date of first heading	Rust		Plant height	Length of lower internode	Diameter of culm	Weight of grain from 100 heads	Weight of 100 culms	Weight of 100 10-cm culm sections	Estimated lodging	Weight required to break 5 culms (average of 20 tests)
				Leaf	Stem								
				Pct.	*Pct.*	*Cm*	*Cm*	*Mm*	*G*	*G*	*G*	*Pct.*	*Lb.*
P1066 × Burbank	20425	10087	May 6	48	5	80	10.1	3.4	101	124	15.1	3	7.66
Clarkan	20400	8858	May 8	45	18	84	11.2	3.3	77	114	12.6	1	6.80
Harvest Queen	15837	6199	do	78	15	84	11.9	3.2	62	109	11.8	0	6.74
Mediterranean selection	3015–105–1	11587	do	8	49	79	9.5	3.1	71	104	12.3	1	6.30
Do	5933–23	11525	May 7	1	24	80	9.3	3.0	73	96	11.3	3	5.96
Fulhard	20420	8257	May 6	51	24	83	10.1	2.8	64	97	11.2	2	5.88
Sibley No. 81	20427	10084	May 9	48	8	71	9.7	2.7	59	82	10.5	1	5.82
Kanred × Kawvale	20409		May 10	5	4	78	10.5	3.0	66	93	11.6	3	5.76
Nebraska No. 28	15836	5147	Apr. 18	83	0	63	8.3	2.7	45	69	10.3	0	5.71
(Kanred × Fulcaster) × (Kanred × Hard Federation)	20405		May 2	11	4	82	11.4	2.9	84	91	10.6	19	5.69
Fulcaster	7082	6471	May 8	60	25	78	9.7	2.8	62	89	10.5	3	5.66
Mediterranean	3015–63		do	3	30	79	10.9	2.8	67	85	10.0	3	5.63
Denton × Kanred			do	15	16	87	12.0	2.9	64	93	9.3	18	5.50
Mediterranean selection	3015–72	11567	May 7	19	34	83	9.4	2.6	53	91	10.9	3	5.46
Kawvale	12577	8180	May 8	7	11	81	11.1	2.9	66	88	10.2	4	5.43
Sutton	15832	10053	do	44	18	76	10.0	2.8	55	89	9.9	3	5.38
White Mediterranean	15834	10023	May 1	85	11	78	11.2	2.7	67	81	10.0	3	5.28
Kanred × Hard Federation	20416	11373	May 2	45	23	83	10.7	2.8	74	83	10.3	18	5.26
Denton	9236	8265	May 9	12	23	85	10.2	2.7	60	86	10.0	4	5.24
Kanred × Fulcaster	20401		May 8	14	3	79	10.8	2.8	56	81	9.8	0	5.16
Mediterranean selection	5933–20	10085	May 5	13	13	74	9.1	2.4	55	76	9.7	13	5.09
Do	3015–81	10086	May 9	13	26	73	8.6	2.6	50	71	9.3	4	4.91
Do	5933–34	11526	May 5	14	1	83	10.3	2.5	50	74	9.2	5	4.86
Quivira	15833	8886	May 1	24	1	87	11.9	2.9	67	90	9.2	4	4.86
Tenmarq × Kawvale	20406		May 6	14	19	79	10.3	2.7	58	78	9.2	3	4.81
Early Blackhull	15838	8856	Apr. 27	75	1	85	10.0	2.7	59	80	9.5	4	4.71
Kanred × Kawvale	20408		May 9	4	0	87	12.2	2.7	47	81	7.8	0	4.62
Blackhull	7172	6251	May 8	85	1	83	10.3	2.6	46	75	8.3	6	4.58
Texas selection	20399		May 9	4	3	83	11.8	2.9	67	85	9.0	8	4.57
Beloglina selection	20424	8884	May 13	74	5	73	11.1	2.7	52	73	8.7	6	4.52
Turkey selection	20370	10094	May 10	95	0	65	9.4	2.6	36	58	8.3	0	4.51
Minturki	20483	6155	May 12	60	65	75	11.2	2.6	39	71	8.3	0	4.47
Denton selection	20350		May 10	39	9	75	11.4	2.8	54	74	9.8	4	4.38
Red May selection	7250–1		May 3	35	19	72	9.2	2.5	50	68	8.2	4	4.38
Kanred	11763	5146	May 10	80	1	80	11.5	2.7	50	72	7.6	4	4.28
Tenmarq	12578	6936	May 7	40	1	81	11.9	2.7	61	74	7.9	3	4.26
Oro	20389	8220	May 10	76	3	81	12.0	2.5	43	67	7.0	0	4.19
Iobred	20430	6934	do	58	10	68	9.6	2.6	39	63	8.4	0	4.13
Kanred selection	20415	10099	do	78	0	63	9.4	2.5	38	52	8.1	0	4.13
Nebraska No. 60	15835	6250	May 13	88	8	74	10.6	2.6	34	64	7.8	0	4.12
Cheyenne	18566	8885	May 10	83	1	78	10.3	2.6	40	61	7.5	0	4.10
Webster × Malakof	20410		do	25	6	78	10.6	2.6	47	64	6.7	14	4.04
Kharkof	16830	1442	May 12	83	9	76	10.9	2.6	34	64	7.4	6	4.03
Turkey selection	20377	11375	May 11	95	0	58	8.3	2.4	27	33	7.0	0	3.84

TABLE 3.—*Breaking strength of straw and various agronomic characters of 129 wheat varieties and strains grown at Denton, Tex., 1934*

Variety or strain	T. S. No.	C. I. No.	Date of first heading	Rust		Plant height	Culms per 8-foot row	Length of lower internode	Diameter of culm	Weight of grain from 100 heads	Weight of 100 culms	Weight of 100 10-cm culm sections	Estimated lodging	Weight required to break 5 culms (average of 20 tests)
				Leaf	Stem									
				Pct.	*Pct.*	*Cm*	*No.*	*Cm*	*Mm*	*G*	*G*	*G*	*Pct.*	*Lb*
Nittany		6962	May 2	40	5	88	194	10.1	3.36	69	119	12.9	....	7.52
Red Chief		3392	May 5	75	5	99	198	11.1	3.42	59	112	11.8	....	7.06
Powerclub		8276	...do....	65	10	100	284	12.6	3.36	72	118	10.8	....	6.71
Clarkan	20400	8858	Apr. 30	76	5	101	299	11.0	3.12	60	105	11.4	0	6.62
Longberry No. 1		5823	May 7	45	20	97	183	11.0	3.36	59	103	11.4	....	6.60
Coppei		4238	May 5	75	5	82	263	11.3	3.38	69	97	10.9	....	6.49
Rupert		5920	May 7	60	15	85	168	8.4	3.20	59	101	12.4	....	6.43
Prosperity		5380	May 12	98	45	74	116	9.3	3.24	45	87	11.6	....	6.35
Red Wave		3500	May 5	75	25	98	220	9.7	3.20	60	103	11.3	....	6.35
Areo		8246	Apr. 26	98	10	93	289	13.6	3.96	65	114	11.8	....	6.29
Fultz-Mediterranean		4811	Apr. 30	95	10	81	201	10.0	3.10	54	85	10.3	....	6.20
Rochester		5693	May 5	95	5	89	220	10.8	3.16	45	98	10.3	....	6.20
Walker		6445	Apr. 27	85	0	100	235	10.6	2.96	48	97	10.4	....	6.17
China		180	May 7	95	20	89	276	10.8	3.20	44	94	11.4	....	6.16
Russian		5737	May 2	75	10	106	314	12.3	3.00	58	103	10.4	15	6.16
Dreadnaught	23048	....	Apr. 27	15	0	90	313	10.5	3.32	65	94	11.1	....	6.15
Purkof		8381	May 5	85	5	97	338	10.8	3.12	60	98	10.9	....	6.07
Democrat		3384	...do....	65	15	92	232	11.5	3.12	50	87	9.6	....	6.05
Rural New Yorker No. 6		5921	May 7	50	10	83	150	11.2	3.38	53	86	10.3	....	5.99
Goldcoin		4156	May 4	45	10	97	278	10.3	3.22	46	94	9.9	....	5.97
Genro		11535	May 7	85	30	72	222	8.4	3.30	56	85	10.5	....	5.96
Imperial Amber		5338	May 5	60	10	93	190	10.1	3.20	50	94	11.3	....	5.96
Nabob		8869	May 3	85	5	95	222	12.0	3.06	48	94	10.6	....	5.91
Jones Fife		4466	...do....	98	10	88	246	12.3	3.42	44	90	10.8	....	5.80
Diehl-Mediterranean		1395	May 5	50	5	100	200	10.9	2.92	54	89	9.9	....	5.80
Greeson		6320	Apr. 30	85	T	86	250	10.2	3.00	59	87	9.9	....	5.73
Eaton		4682	May 17	100	20	69	184	9.7	3.32	28	88	11.5	....	5.69
P1066×Burbank	20425	10087	Apr. 30	50	5	86	260	9.7	3.10	61	84	10.3	11	5.67
Denton×Kanred	23051	....	May 3	50	5	104	350	11.5	3.12	61	100	10.0	56	5.65
V. P. I. 131		10047	Apr. 30	85	5	89	216	10.8	2.96	51	82	10.3	....	5.65
Goens		4857	...do....	75	T	91	282	9.0	2.90	49	71	10.3	....	5.58
Leap		4823	Apr. 23	75	0	85	220	10.6	3.20	57	89	10.3	....	5.55
Honor		6161	Apr. 30	95	10	99	327	9.8	3.10	49	95	10.5	....	5.52
Triplet		5408	May 5	98	5	99	252	11.1	3.42	59	112	11.8	....	5.52
Dawson		3342	Apr. 30	98	5	95	330	8.3	3.14	49	78	10.3	....	5.50
Silvercoin		6013	May 5	45	10	90	268	12.3	3.28	45	91	9.3	....	5.49
Red May		5336	May 2	95	5	79	170	7.6	3.06	38	73	10.2	....	5.43
Gypsy		3436	May 7	85	5	80	174	9.2	2.98	49	72	10.1	....	5.42
Genesee Giant		1744	Apr. 26	85	10	74	163	9.9	3.14	48	69	9.5	....	5.36
Quivira	15833	8886	...do....	65	T	88	363	10.1	2.90	59	75	9.3	5	5.30
Denton	9236	8265	May 1	34	5	95	335	10.9	2.78	48	83	9.1	8	5.29
Harvest Queen	15837	6199	May 3	85	10	96	290	12.9	3.08	40	81	8.5	1	5.27
Russian Red		5028	May 5	95	25	90	232	10.7	3.18	55	90	10.1	....	5.26
Sol		6009	May 16	65	25	70	178	9.7	3.46	40	89	11.4	....	5.24
Red Clawson		3393	May 2	95	5	86	222	10.7	3.22	50	79	10.1	....	5.24
Mediterranean selection	5933–23	11523	Apr. 30	5	10	97	290	12.1	2.76	45	80	8.9	4	5.17
Oakley		6301	Apr. 23	75	5	72	192	8.1	2.70	41	69	8.5	....	5.16
Texas selection	20399	....	May 6	5	10	81	242	11.3	2.88	54	68	8.7	50	5.14
Illini Chief		5406	Apr. 30	95	T	85	246	11.0	2.96	46	77	8.9	....	5.12
White Winter		5219	May 17	99	20	77	216	10.1	3.00	37	87	9.2	....	5.11
Mediterranean	3015–63	....	Apr. 30	50	5	100	306	12.6	2.78	47	84	8.3	5	5.08
Portage		5654	May 5	50	10	93	227	11.4	3.20	50	89	9.1	....	5.06
Forward		6691	May 2	55	5	91	276	13.3	2.98	54	82	9.1	....	5.04
Fishhead × Velvet Chaff 51	23047	....	Apr. 17	65	0	70	154	9.6	3.16	73	73	9.6	....	5.04
Odessa		4475	May 5	75	20	86	206	9.9	3.00	48	88	10.5	....	5.02
Mealy		3358	Apr. 30	99	10	91	293	10.5	2.94	51	84	9.6	....	5.02
Berkeley Rock		8272	May 7	75	5	86	242	8.8	2.88	40	75	9.3	....	5.02
Golden		10063	May 6	45	20	81	252	10.8	3.30	45	80	10.1	....	5.02
Currell		3326	Apr. 30	70	5	88	233	10.5	2.98	49	81	9.5	....	5.00
Hybrid 128		4512	May 9	99	20	80	232	7.5	2.96	38	76	9.1	....	4.98
Valley		5923	May 7	85	15	83	209	11.2	2.80	39	74	9.6	....	4.97
Rice		5734	Apr. 18	85	0	79	254	10.6	2.84	50	74	9.4	....	4.95
Tenmarq × Kawvale	20406	....	May 1	20	0	90	354	11.2	2.90	52	74	9.1	8	4.94
Mosida		6688	May 2	99	5	79	240	9.3	2.76	45	71	8.9	....	4.94

TABLE 3.—*Breaking strength of straw and various agronomic characters of 129 wheat varieties and strains grown at Denton, Tex., 1934*—Continued

Variety or strain	T. S. No.	C. I. No.	Date of first heading	Rust		Plant height	Culms per 8-foot row	Length of lower internode	Diameter of culm	Weight of grain from 100 heads	Weight of 100 culms	Weight of 100 10-cm culm sections	Estimated lodging	Weight required to break 5 culms (average of 20 tests)
				Leaf	Stem									
				Pct.	*Pct.*	*Cm*	*No.*	*Cm*	*Mm*	*G*	*G*	*G*	*Pct.*	*Lb.*
Mediterranean selection	3015–81	10086	Apr. 27	65	5	90	348	9.6	2.66	40	71	8.6	5	4.93
Sutton	15832	10053	May 3	30	10	90	314	11.0	2.80	44	79	8.5	5	4.93
Fishhead × Velvet Chaff	23042	----	Apr. 19	65	0	78	182	9.0	3.18	77	90	10.8	----	4.92
Kanred × Fulcaster selection	20401	----	May 5	10	0	88	356	11.1	2.94	53	71	8.4	3	4.86
Shepherd	----	6163	Apr. 30	95	T	81	211	9.2	2.88	46	76	9.3	----	4.84
Minturki	----	6155	May 6	75	0	81	238	9.3	2.34	36	62	8.4	----	4.82
Kinney	----	5189	May 3	65	10	81	356	9.6	2.76	42	69	8.3	----	4.82
Michikof	----	6990	May 5	99	15	89	256	10.2	2.70	41	75	8.3	----	4.81
Mediterranean selection	5933–20	10085	Apr. 26	40	10	83	330	9.8	2.46	38	62	7.3	18	4.81
Redhart	----	8898	Apr. 23	85	0	84	270	9.2	2.96	51	76	8.9	----	4.80
Red Indian	----	8382	May 6	55	5	81	228	10.4	2.36	47	67	8.8	----	4.80
Mammoth Red	----	2008	June 7	85	15	83	166	9.5	2.34	42	74	9.1	----	4.79
Kofod	----	4337	May 2	75	10	91	256	11.3	2.90	45	78	8.3	----	4.78
Wheedling	----	4846	May 5	95	5	80	202	9.2	2.98	42	79	10.1	----	4.75
Fulhio	----	6999	May 2	85	T	90	206	10.9	2.94	46	79	8.9	----	4.74
Gladden	----	5644	...do....	65	25	74	206	10.1	2.92	43	65	8.4	----	4.74
White Mediterranean	15834	10023	Apr. 25	99	10	81	284	10.9	2.68	49	69	8.1	44	4.74
Rudy	----	4873	May 4	85	5	103	271	11.3	3.00	52	88	9.1	----	4.73
Gold Drop	----	6316	Apr. 18	85	5	76	236	10.2	2.64	47	69	8.1	----	4.73
Gasta	----	11398	Apr. 20	65	0	78	288	9.4	2.54	45	67	8.4	----	4.71
Kanred × Hard Federation	20416	11373	Apr. 27	75	5	80	346	10.2	2.84	49	65	8.3	3	4.71
Sibley No. 81	20427	10084	May 5	65	5	94	292	10.9	2.80	47	73	8.5	26	4.71
Nigger	----	5366	...do....	85	5	78	206	9.7	2.94	40	68	8.7	----	4.68
Red Rock	----	5597	May 3	75	T	87	292	9.3	2.80	42	65	8.5	----	4.65
Mediterranean selection	5933–34	11526	Apr. 27	40	5	82	362	10.8	2.36	37	58	7.1	16	4.60
Poole	----	3488	May 5	95	10	90	214	11.7	3.02	39	74	8.2	----	4.56
Kanred selection	20415	10099	...do....	50	5	81	288	11.4	2.72	50	60	7.5	33	4.54
Cooperatorka	----	8861	May 2	99	0	81	321	9.8	2.62	35	62	8.1	----	4.49
Minhardi	----	5149	Apr. 18	75	0	82	230	9.9	2.96	48	75	9.3	----	4.48
Fishhead × Velvet Chaff	23046	----	Apr. 17	65	0	73	204	10.3	2.92	68	65	8.9	----	4.47
Kawvale	12577	8180	May 3	15	0	94	370	11.6	2.88	48	76	8.4	1	4.41
(Kanred × Fulcaster) × (Kanred × Hard Federation)	20405	----	Apr. 25	25	5	87	359	12.7	2.78	60	69	7.3	28	4.38
Early Blackhull	15838	8856	Apr. 23	85	2	77	239	9.2	2.50	43	54	7.5	15	4.37
Fultz	20474	3416	Apr. 20	75	0	78	274	11.3	2.80	43	68	8.1	61	4.33
Tenmarq	12578	6936	May 3	70	T	88	333	10.7	2.80	49	69	8.1	21	4.33
Trumbull	----	5657	May 5	95	5	74	197	10.7	2.72	40	65	7.6	----	4.32
Fulcaster	7082	6471	May 3	60	10	89	284	11.2	2.52	42	64	6.9	6	4.32
Flint	----	6307	Apr. 20	75	0	85	315	11.4	2.84	48	74	7.8	0	4.31
Purplestraw	----	1915	Apr. 19	95	0	72	322	9.4	2.38	42	56	7.7	----	4.28
Ridit	----	6703	May 3	99	5	90	292	11.4	2.60	39	68	7.0	----	4.27
Mediterranean selection	3015–105–1	11587	Apr. 29	20	5	95	344	10.6	2.80	48	73	7.9	18	4.26
Zimmerman	----	2907	Apr. 18	65	0	79	244	9.7	2.78	44	69	8.3	----	4.23
Fulhard	20420	8257	May 5	99	0	79	282	9.4	2.68	37	57	7.8	4	4.22
Webster × Malakof	20410	----	...do....	40	0	102	295	13.5	2.88	53	74	7.8	78	4.20
Ashkof	----	6680	May 8	65	5	77	232	11.0	2.72	33	57	7.5	----	4.12
Beloglina selection	20424	8884	May 9	60	0	77	312	11.1	2.52	45	56	6.4	31	4.11
White Odessa	----	4655	May 7	95	10	78	272	10.4	2.62	30	60	7.3	----	3.99
Mediterranean selection	3015–72	11567	Apr. 29	45	5	91	334	11.3	2.22	40	63	7.3	10	3.97
Windsor	----	5915	May 2	85	30	61	228	7.0	2.74	31	51	7.6	----	3.95
Iobred	20430	6934	May 7	99	10	80	243	11.7	2.66	30	57	7.1	----	3.94
Blackhull	7172	6251	May 2	85	5	84	352	9.8	2.52	34	59	6.9	26	3.88
Cheyenne	18566	8885	May 6	85	T	71	310	10.3	2.68	36	49	7.1	8	3.86
Kanred	11763	5146	...do....	60	0	89	354	12.1	2.62	43	62	6.3	73	3.82
Alton	----	1438	May 7	99	10	85	308	11.8	2.60	39	61	6.6	13	3.79
Ashland	----	6692	May 5	95	T	78	266	10.9	2.60	32	55	7.1	----	3.78
Prohibition	----	4068	May 8	85	T	65	283	14.8	3.22	36	66	9.3	----	3.77

TABLE 3.—*Breaking strength of straw and various agronomic characters of 129 wheat varieties and strains grown at Denton, Tex., 1934*—Continued

Variety or strain	T. S. No.	C. I. No.	Date of first heading	Rust		Plant height	Culms per 6-foot row	Length of lower internode	Diameter of culm	Weight of grain from 100 heads	Weight of 100 culms	Weight of 100 10-cm. culm sections	Estimated lodging	Weight required to break 5 culms (average of 20 tests)
				Leaf	Stem									
				Pct.	*Pct.*	*Cm*	*No.*	*Cm*	*Mm*	*G.*	*G*	*G*	*Pct.*	*Lb.*
Oro	20389	8220	May 6	85	T	71	276	10.3	2.48	37	47	6.4	...	3.76
Nebraska No. 60	15835	6250	May 7	98	T	73	244	10.0	2.52	36	49	6.2	16	3.69
Sherman	...	4430	May 8	98	5	70	276	11.2	2.48	32	46	6.0	...	3.57
Wisconsin Pedigree No. 2	...	6683	May 7	98	T	78	272	9.2	2.54	27	51	6.5	...	3.51
Turkey	...	1558	May 8	85	T	67	332	8.5	2.38	34	40	6.1	...	3.48
Nebraska No. 28	15836	5147	Apr. 15	85	0	66	297	9.8	2.44	39	48	6.8	0	3.48
Huston	...	5208	Apr. 23	99	5	66	259	8.9	2.36	27	40	6.3	...	3.36
Early Kanred	...	8261	Apr. 14	85	0	67	298	9.3	2.20	38	42	6.6	...	3.30
Kharkof	16830	1442	May 6	85	0	70	292	11.4	2.36	32	42	5.1	26	3.21

TABLE 4.—*Analysis of variance of strength of straw determinations of winter wheat varieties grown at Denton, Tex., 1932, 1933, and 1934*

Variance	Degrees of freedom	Sum of squares	Mean square	Standard error of the mean of any variety	Least significant difference between any two varieties
1932				*Pounds*	*Pounds*
Total	1,299	892.612	0.687		
Between varieties	64	571.085	8.923	0.114	0.316
Within varieties	1,235	321.527	.260		
1933					
Total	879	1,068.087	1.215		
Between varieties	43	617.146	14.352	.164	.455
Within varieties	836	450.941	.539		
1934					
Total	2,579	3,106.018	1.204		
Between varieties	128	1,886.830	14.741	.158	.438
Within varieties	2,451	1,219.188	.497		

It will be noted that the varieties differed markedly with respect to most of the characters. Thus, in the seasons when these relations were studied the following differences existed: In 1933 and 1934 (tables 2 and 3) the highest value for the weight of grain per 100 heads exceeded that of the lowest by 274 and 185 percent, respectively; the highest weight of 100 culms, by 276 and 198 percent; and the greatest weight per unit length of culm, by 125 and 153 percent. During 1932–34 (tables 1–3) the highest breaking strength of straw exceeded the lowest by 86, 99, and 134 percent, respectively; in length of lower internode the highest values exceeded the lowest by 61, 47, and 94 percent; and the greatest diameter of culm at base exceeded the lowest by 45, 42, and 80 percent. The range in date of maturity was 17 days in 1932, 25 days in 1933, and 33 days in 1934. Table 4 shows that the range in breaking strength of straw was many times greater than the standard error. Statistical analysis of the other determinations was not attempted.

TABLE 5.—*Correlation coefficients for each pair of characters studied in winter wheat varieties grown at Denton, Tex., in 1932, 1933, and 1934*

Year and characters	Breaking strength of straw	Height of plant	Lower internode (length)	Culm at base (diameter)	Date of maturity	Grain from 100 heads (weight)	100 culms (weight)	Unit length of culm at base (weight)	Stand (culms per 8-foot row)
1932 [1]									
Lodging in the field	−0.046	0.286	0.159	−0.063	0.259				
Breaking strength of straw		.613	.253	.861	−.112				
Height of plant			.479	.682	.322				
Length of lower internode				.501	.216				
Diameter of culm at base					−.056				
1933 [2]									
Lodging in the field	.025	.327	.208	.023	−.209	0.347	0.126	0.003	
Breaking strength of straw		.348	.004	.903	−.355	.788	.895	.956	
Height of plant			.664	.382	.086	.563	.662	.294	
Length of lower internode				.236	.267	.250	.292	.078	
Diameter of culm at base					.023	.896	.964	.887	
Date of maturity						−.256	−.229	−.353	
Weight of grain from 100 heads							.871	.814	
Weight of 100 culms								.869	
1934 [3]									
Lodging in the field	−.196	.056	.351	−.001	.178	.158	−.575	−.210	−0.039
Breaking strength of straw		.542	−.411	.789	.152	.544	.901	.911	−.330
Height of plant			.435	.423	.129	.142	.672	.431	.296
Length of lower internode				.249	.114	−.183	.229	−.010	.342
Diameter of culm at base					.238	.324	.811	.868	−.396
Date of maturity						−.478	.153	.143	−.213
Weight of grain from 100 heads							.648	.524	−.433
Weight of 100 culms								.893	−.317
Weight per unit length of culm at base									−.518

[1] Least significant value of $r=0.250$; least highly significant value of $r=0.325$.
[2] Least significant value of $r=0.288$; least highly significant value of $r=0.372$.
[3] Least significant value of $r=0.195$; least highly significant value of $r=0.254$, except for lodging, in which case the coefficient was calculated for 40 varieties only. For these cases the least significant value of $r=0.304$.

The chief interest here is with respect to lodging, since the tendency to lodge is the factor it is desirable to measure. All but 3 of the 65 varieties and strains grown in 1932 showed some tendency to lodge, the amount of lodging varying from a trace to 64 percent. In 1933, 32 of the 44 varieties and strains showed a tendency to lodge, but the amount of lodging was small, varying from 1 to 19 percent. No lodging occurred in the planting made for strength of straw studies in 1934. However, 39 of the varieties and strains were also included in the replicated yield nursery, and it was from these plantings that lodging data were taken in that year. In this case all but three varieties showed a tendency to lodge, the amount of lodging varying from 1 to 73 percent. It must be admitted that the data on lodging are not so satisfactory as might be desired, but, on the other hand, they are probably as good as can reasonably be expected, if due consideration is given to seasonal variation and the numerous factors known to affect lodging. On the whole, it would seem that the range in lodging and of other characters studied is such as to make a study of the relation of these characters and tendency to lodge at least fairly satisfactory. It now remains to be determined whether lodging is correlated with any of the plant characters that were studied, and if so to what extent.

LODGING AND BREAKING STRENGTH OF STRAW

Lodging was not significantly correlated with breaking strength of straw in any season (table 5). It was significantly and positively correlated with height of plant in 1932 and 1933, with length of the lower internode in 1934, with date of maturity in 1932, and with weight of grain per 100 heads in 1933, and was significantly and negatively correlated with weight per 100 culms in 1934. All other coefficients involving lodging failed to reach the level of significance. The coefficients for lodging and length of the lower internode were positive in each of the three seasons, and in one of them statistically significant. When combined by Fisher's method (*5*) a coefficient of 0.226 was obtained, which was highly significant.

Because of the influence of these various factors on lodging, it was considered desirable to determine whether, by holding these constant by means of partial correlation coefficients, the relation between breaking strength and lodging might be made more apparent. It was found that this procedure made no material changes in the coefficients for 1932 and 1933, and hence the partial correlation coefficients for those years are not given in detail. The coefficients for 1934 are as follows:

Characters held constant	*Partial coefficient*
Height of plant	−0.270
Length of lower internode	−.061
Date of maturity	−.229
Height of plant and length of lower internode	−.011
Height of plant and date of maturity	−.291
Length of lower internode and date of maturity	−.110

It will be noted that, whereas the simple correlation coefficient between breaking strength and lodging was −0.196, the partial coefficient with height of plant constant was −0.270. Similarly, this coefficient was increased to −0.229 by holding date of maturity constant and to −0.291 by holding both height of plant and date of maturity constant. None of these values, however, reaches the level of statistical significance (0.304). On the other hand, holding length of internode constant decreased the coefficient.

One of the serious difficulties in evaluating the tendency of varieties to lodge is the very great variation in lodging from year to year and from place to place. It would seem, therefore, that an average for a number of years might be useful. Eighteen varieties were grown at Denton in each of the 4 years, 1931–34, and 36 were grown in each of the 2 years, 1933–34. The correlation coefficient for average lodging and for average breaking strength was −0.626 for the 18 varieties for the 4-year period, and −0.387 for the 36 varieties for the 2-year period, both coefficients being statistically significant.

Additional information is afforded by a number of varieties grown at different experiment stations, mostly midwestern, the lodging data for which have been supplied by the agricultural experiment stations of the respective States. Table 6 gives these data, together with lodging, breaking strength of straw, and the weight per unit length of culm for the same varieties grown at Denton. Since all varieties were not grown each year, the average lodging of each variety is expressed as a percentage of the average lodging of the single variety, Blackhull, for the same years. This places all varieties on a comparable basis so far as this is possible. The correlation coefficient for lodging and breaking strength is −0.422, which is highly significant.

TABLE 6.—*Comparison of field lodging of wheat varieties grown at selected experiment stations with breaking strength and weight per unit length of culm at Denton, Tex.*

Variety	T. S. No.	C. I. No.	Percentage of lodging during indicated year at—																								Average	Average expressed as percentage of lodging in Blackhull (same experiments)	Average percentage of lodging in Blackhull (same experiments)	Crop years compared	Denton, Tex., 1934	
			Denton, Tex.				Manhattan, Kans.								Urbana, Ill.		New Brunswick, N. J.		Bozeman, Mont.				Lincoln, Nebr.		Woodward, Okla.	Fort Collins, Colo.							Breaking strength of culm	Weight per unit of culm
																	Nursery	Field plot															
			1931	1932	1933	1934	1927	1928	1929	1930	1931	1932	1934	1935	1924	1931	1928	1928	1931	1933	1934	1935	1932	1935	1935	1934	1935						
			Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*				*No.*	*Lb.*	*G*
Nittany		6962											0	5										1			2.0	12.3	16.3	3	7.52	12.9
Clarkan	20400	8858	1	0	1	0			35	45	55	18	0	3										15		3	14.7	43.5	33.8	12	6.62	11.4
Dreadnaught	23048									0		0		0													.0	.0	53.0	3	6.15	11.1
Purkof		8381								25	52	0	0	15		10	5	27						0			14.9	30.9	48.2	9	6.07	10.9
Democrat		3384									15	8						20									14.3	25.9	55.3	3	6.05	9.6
P1066 × Burbank	20425	10087		9	3	11					50	15	10	4						0			0	0	5	49	5	12.4	40.8	30.4	13	5.67	10.3
Leap		4823									7		0	0			5	42						0			9.0	25.7	35.0	6	5.58	10.3
Red May		5336	2	9	4	5											30										10.0	51.0	19.6	5	5.43	10.2
Quivira	15833	8886	2	9	4	5	46	37	67	83	85	22	3	7					5	0	7	15		5	11		22.9	58.4	39.2	18	5.30	9.3
Denton	9236	8265	4	9	4	8							10	10											9		7.7	59.2	13.0	7	5.29	9.1
Harvest Queen	15837	6199	1	1	0	1	77	18	54	58	50	23	25	32	25	80	10							3	5		27.2	69.6	39.1	17	5.27	8.5
Mediterranean selection	5933–23	11525	1	10	3	4																		70			17.6	110.0	16.0	5	5.17	8.9
Do	3015–63		4	9	3	5																					5.3	35.6	14.5	4	5.08	8.3
Forward		6691											0	3	0		5	23						0			5.2	19.5	26.7	6	5.04	9.1
Berkeley Rock		8272													25		5										15.0	45.2	32.5	2	5.02	9.3
Currell		3326						23	25	15			8	15			10	24						14			16.8	40.1	41.9	8	5.00	9.5
Hybrid 128		4512								0		0						10									3.3	5.5	60.0	3	4.98	9.1
Valley		5923													15	90	5										35.7	71.0	51.7	3	4.97	9.6
Mediterranean selection	3015–81	10086	7	33	4	5						8															11.4	55.3	20.6	5	4.93	8.6

TABLE 6.—*Comparison of field lodging of wheat varieties grown at selected experiment stations with breaking strength and weight per unit length of culm at Denton, Tex.*—Continued

Variety	T. S. No.	C.I. No.	Percentage of lodging during indicated year at—																								Average	Average expressed as percentage of lodging in Blackhull (same experiments)	Average percentage of lodging in Blackhull (same experiments)	Crop years compared	Denton, Tex., 1934	
			Denton, Tex.				Manhattan, Kans.								Urbana, Ill.		New Brunswick, N. J.		Bozeman, Mont.				Lincoln, Nebr.		Woodward, Okla.	Fort Collins, Colo.							Breaking strength of culm	Weight per unit of culm
																	Nursery	Field plot															
			1931	1932	1933	1934	1927	1928	1929	1930	1931	1932	1934	1935	1924	1931	1928	1928	1931	1933	1934	1935	1932	1935	1935	1934	1935						
			Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*No.*	*Lbs.*	*G*
Sutton	15832	10053	4	13	3	5																					6.3	43.4	14.5	4	4.93	8.5
Kanred × Fulcaster selection	20401		2	3	0	3																					2.0	13.8	14.5	4	4.86	8.4
Shepherd		6163								0	0						20										6.7	9.9	68.0	3	4.84	9.3
Minturki	20483	6155					72	0	0	27		6	0	3			60	20		23	2	30	77		40			25.7	51.7	49.7	14	4.82	8.4
Michikof		6990						0	52	50					10	80	20	46									36.9	64.4	57.3	7	4.81	8.3
Mediterranean selection	5933–20	10085	6	13	13	18						14	13												82		22.7	83.8	27.1	7	4.81	7.3
Mammoth Red		2008									15						25							0			20.0	34.8	57.5	2	4.79	9.1
Fulhio		6999											0	3	0									0			.8	4.4	18.5	4	4.74	8.9
Gladden		5644											0	0	0	0	5							0			.8	2.4	34.0	6	4.74	8.4
White Mediterranean	15834	10023		16	3	44																					19.0	109.8	17.3	3	4.74	8.1
Kanred × Hard Federation	20416	11373		4	18	3		5	72	81	68	12	0	0						0	0	18		0	4	28	29	20.1	46.9	42.9	17	4.71	8.3
Sibley No. 81	20427	10084		18	1	26						23	23	28											34			21.9	117.8	18.6	7	4.71	8.5
Red Rock		5597									10		0	10				30	13					5				11.3	32.3	35.0	6	4.65	8.5
Mediterranean selection	5933–34	11526	5	9	5	16							0	20	0		10	19						0			8.8	60.7	14.5	4	4.60	7.1
Poole		3488						0																			7.0	26.2	26.7	7	4.56	8.2
Kanred selection	20415	10099		28	T [1]	33						23	7	32										64	39	96	52	37.4	125.9	29.7	10	4.54	7.5
Cooperatorka		8861						0	91	72	62	17	0	20											19			35.1	79.6	44.1	8	4.49	8.1
Minhardi		5149							0	0		0	0	2		10	5		12	0	0	93		5				10.6	21.5	49.4	12	4.48	9.3

Kawvale	12577	8180	1	1	0	0	----	25	75	83	70	12	0	6	----	----	----	----	9	0	----	----	----	40	21	----	----	22.9	69.6	32.9	15	4.41	8.4
Early Blackhull	15838	8856	4	2	4	15	----	35	93	75	----	30	0	4	----	----	----	----	37	----	----	----	0	3	4	65	59	26.9	79.6	33.8	16	4.37	7.5
Fultz	20474	3416	6	4	----	61	----	0	----	70	20	----	0	----	----	----	10	42	----	----	----	----	----	25	8	----	----	23.7	64.4	36.8	9	4.33	8.1
Tenmarq	12578	6936	2	13	3	21	69	28	81	86	58	11	2	7	----	40	----	----	20	----	----	----	----	25	8	----	----	29.6	74.4	39.8	16	4.33	8.1
Trumbull	----	5657	----	----	----	----	----	----	----	----	----	----	0	3	0	----	10	19	----	----	----	----	----	0	----	----	----	30.9	80.9	38.2	19	4.32	6.9
Fulcaster	7082	6471	2	8	3	6	72	35	82	68	67	----	0	23	15	----	40	----	28	0	17	93	----	5	23	----	----	15.1	34.7	43.5	12	4.27	7.0
Ridit	----	6703	----	----	----	----	73	0	----	0	----	0	0	5	----	----	20	----	17	0	0	43	----	23	----	----	----	46.0	287.5	16.0	2	4.20	7.8
Mediterranean selection	3015–11587	105–1	1	21	1	18	----	----	----	----	----	----	0	18	----	----	----	----	----	----	----	----	0	47	15	57	26	20.4	79.1	25.8	10	4.26	7.9
Fulhard	20420	8257	----	5	2	4	----	34	88	84	43	6	0	29	----	----	----	----	----	----	----	----	0	2	16	50	46	27.3	71.7	38.1	15	4.225	7.8
Webster×Malakof selection	20410	----	----	----	----	14	78	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	46.0	287.5	16.0	2	4.20	7.8
Beloglina selection	20424	8884	----	35	6	31	----	----	----	50	80	28	10	----	----	----	----	----	37	2	----	----	0	----	28	86	----	32.8	94.8	34.6	12	4.11	6.4
Mediterranean selection	3015–72	----	5	39	9	10	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	15.8	109.0	14.5	4	3.97	7.3
Iobred	20430	6934	----	----	0	----	----	70	0	40	----	----	0	20	----	100	10	----	----	----	----	----	----	----	----	----	----	30.0	66.1	45.4	8	3.94	7.1
Cheyenne	18566	8885	----	6	0	8	----	----	----	78	48	10	0	3	----	----	----	----	4	0	17	42	----	12	20	----	----	17.7	48.4	36.6	14	3.86	7.1
Blackhull	7172	6251	6	20	6	26	76	27	84	89	75	45	2	25	25	90	40	46	38	23	40	95	0	22	6	85	60	42.0	100.0	----	25	3.88	6.9
Kanred	11763	5146	5	35	4	73	76	53	89	93	74	45	23	45	75	100	50	----	----	----	33	98	----	56	18	----	----	55.0	130.6	42.1	19	3.82	6.3
Oro	20389	8220	----	6	0	----	----	22	79	72	83	6	----	9	----	----	----	----	6	1	0	75	----	65	13	----	----	21.2	73.4	42.5	14	3.76	6.4
Nebraska No. 60	15835	6250	1	19	0	16	70	0	60	----	48	22	7	33	----	----	----	----	35	0	33	95	37	17	18	56	15	29.1	76.4	38.1	20	3.69	6.2
Wisconsin Pedigree No. 2	----	6683	----	----	----	----	----	----	----	----	----	----	0	20	----	70	----	50	----	----	----	----	----	44	----	----	----	36.8	99.5	37.0	5	3.51	6.5
Turkey	----	1558	----	----	----	----	69	28	81	86	58	11	22	53	15	100	15	----	----	----	----	----	----	----	29	----	----	47.3	97.1	48.7	12	3.48	6.1
Nebraska No. 28	15836	5147	4	0	0	0	61	31	63	----	----	----	0	0	----	----	5	----	----	----	----	----	----	0	----	----	----	14.9	49.0	30.4	11	3.48	6.8
Early Kanred	----	8261	----	----	----	----	88	78	85	71	70	----	----	----	----	----	----	----	----	----	----	----	----	----	0	----	----	65.3	109.7	59.5	6	3.30	6.6
Kharkof	16830	1442	4	10	6	26	72	22	78	77	82	23	3	45	----	----	----	----	21	0	7	87	----	13	31	78	53	36.9	86.8	42.5	20	3.21	5.1

[1] T=trace.

Table 7 presents data on lodging from the uniform variety yield tests of winter wheat in the Great Plains, sponsored by the United States Department of Agriculture. In this case the averages for lodging were calculated in percentages of Kharkof, a variety common to all tests. The correlation coefficient for lodging and breaking strength was -0.575, which is well above the 0.05 point (0.468) but not equal to the 0.01 point (0.590).

TABLE 7.—*Field lodging of hard red winter wheat varieties in uniform yield nursery tests at eight experiment stations, 1931–35* [1]

Variety	T. S. No.	C. I. No.	Percentage of lodging during indicated year at—																				Average	Average expressed as percentage of Kharkof (same experiments)	Average lodging in percentage of Kharkof (same experiments)	Crop years compared	Denton, Tex., 1933–34	
			Denton, Tex.			Goodwell, Okla.		Manhattan, Kans.							Akron, Colo.		Bozeman, Mont.				Lincoln, Nebr.	North Platte, Nebr.	Waseca, Minn.						Breaking strength of culm	Weight per culm
			1931	1932	1934	1931	1932	1927	9128	1929	1930	1931	1932	1935	1934	1935	1931	1933	1934	1935	1935	1935	1932	1933	1935						
			Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*			*No.*	*Lb.*	*G*
Kharkof	16830	1442	5	25	29	1	2	1	4	34	10	23	42	8	0	1	17	3	97	73	76	0	100	0	32	25.3	100.0			23	3.62	7.0
Kanred	11763	5146	11	25	26	2	2	13	17	36	7	36	81	20	0	1	22	2			80	15	100	17	43	26.5	134.5	19.7	21	4.05	7.0
Nebraska No. 60	15835	6250	5	20	9	T	2					8	58	17	0	1	17	2	93	75	87	0	100	0	41	28.2	100.4	28.1	19	3.91	6.3
Tenmarq	12578	6936	4	10	6	2	2	9	1	15	0	3	38	8	1	0					33	40				10.8	66.3	16.3	16	4.30	8.0
Blackhull	7172	6251	3	19	13	2	2	15	7	26	11	8	87	7	1	0					54	38				18.3	112.3	16.3	16	4.23	7.6
Early Blackhull	15838	8856	15		8	16	3		7	21	7	23	48	5	27	0					28					16.0	88.4	18.1	13	4.54	8.5
Quivira	15833	8886	8	11	5	2	4		1	18	0	10	2	13	1	0		4			22					6.7	38.3	17.5	15	5.08	9.3
Cheyenne	18566	8885									0	12	17	0	0	0			67	33	36	0				16.5	50.0	33.0	10	3.98	7.3
Oro		8220						0	3	6	7	38	55	0	0	0			90	67	66	3				25.8	90.9	28.4	13	3.98	6.7
Turkey		1558						1	4	43	10	23	63	13												22.4	128.7	17.4	7	3.48	6.1
Kanred×Marquis		10090																												
Cooperatorka		8861																												
Minturki		6155										18	12	5	0	0	6	0	63	70	66	1	50	0	50	24.4	72.4	33.7	14	4.65	8.4
Turkey selection	20374	10016												0	0	0			100	68	48	13			49	34.8	96.9	35.9	8	3.45	7.2
Clarkan	20400	8858			3							32	50	12							17					22.8	64.0	35.6	5	6.71	12.0
Kawvale	12597	8180	0	T	1	2	2	10	0	10	10	0	17	0							48					7.7	38.5	20.0	13	4.92	9.3
Harvest Queen	15837	6199	4	3	6	4	3	1	0	9	3	10	53	17												9.4	61.4	15.3	12	6.01	10.2
Fulcaster	7082	6471	4	24	9	2	2	8	0	19	7	17	35	17												12.0	78.4	15.3	12	4.99	8.7
Nebraska No. 28	15836	5147	3	0		6	5																			3.5	42.2	8.3	4	4.60	8.6
Denton	9236	8265	5	2	3	2	2																			2.8	22.5	12.4	5	5.27	9.6

[1] QUISENBERRY, K. S. COMPARISON OF WINTER WHEAT VARIETIES GROWN IN COOPERATIVE PLOT AND NURSERY EXPERIMENTS IN THE HARD RED WINTER WHEAT REGION IN 1931, 1932, 1933, 1934, and 1935. U. S. Bureau Plant Industry, Division Cereal Crops and Diseases. [Unnumb. Pubs.] [Mimeographed.]

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Further data are presented in table 8 for a different group of varieties grown at Pullman, Wash., Logan and Newton, Utah, Corvallis, Oreg., and New Brunswick, N. J. The averages for lodging were calculated in the same way as in the foregoing tests; Hybrid 128 was used as a standard of comparison.

TABLE 8.—*Comparison of lodging of wheat varieties for selected years and stations in the United States with strength of straw at Denton, Tex., 1934*

Variety	C. I. No.	Percentage of lodging during indicated year at—																		Average	Average expressed as percentage of lodging in Hybrid 128 (same experiments)	Average percentage of lodging in Hybrid 128 (same experiments)	Crop years compared	Denton, Tex., 1934	
		Pullman, Wash.									Logan, Utah				Newton, Utah				New Brunswick, N. J.	Corvallis, Oreg.					
		Field plot test				Nursery test																		Breaking strength of culm	Weight per unit of culms
		1931	1932	1933	1934	1930	1931	1932	1933	1934	1931	1932	1933	1934	1931	1932	1933	1934	1928	1933					
		Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*No.*	*Lb.*	*G*
Coppei	4238	0	0	0	----	0	1	7	0	----	----	----	----	----	----	----	----	----	5	----	1.6	88.9	1.8	8	6.49	10.9
Goldcoin	4156	----	----	----	----	----	----	----	----	----	16	12	20	8	----	----	----	----	5	0	10.2	100.0	10.2	6	5.97	9.9
Jones Fife	4466	0	14	2	49	3	3	4	2	100	----	----	----	----	----	----	----	----	----	----	19.7	88.3	22.3	9	5.80	10.8
Triplet	5408	0	2	2	55	3	33	4	2	100	15	23	17	13	15	23	17	13	20	20	18.3	110.9	16.5	19	5.52	11.8
Silvercoin	6013	----	----	----	----	----	----	----	----	----	16	10	17	8	----	----	----	----	10	----	12.2	100.0	12.2	5	5.49	9.3
White Winter	5219	----	----	----	----	----	0	0	1	----	----	----	----	----	15	15	17	----	----	0	6.9	113.1	6.1	7	5.11	9.2
Odessa	4475	----	----	----	----	----	----	----	----	----	21	25	22	----	----	----	----	----	30	----	24.5	184.2	13.3	4	5.02	10.5
Golden	1003	----	2	0	100	0	6	8	0	100	17	20	8	----	----	17	20	8	----	0	20.4	107.9	18.9	15	5.02	10.1
Hybrid 128	4512	1	2	0	97	0	0	0	1	100	17	7	19	8	10	13	19	9	10	0	16.5	100.0	----	19	4.98	9.1
Mosida	6688	----	----	----	----	1	0	13	2	98	----	----	----	----	----	----	----	----	20	----	22.3	120.5	18.5	6	4.94	8.9
Ridit	6703	4	3	2	100	0	1	17	2	100	16	18	20	15	17	18	20	15	20	25	21.7	131.5	16.5	19	4.27	7.0
White Odessa	4655	----	----	----	----	3	0	9	2	100	22	16	17	----	----	----	----	----	5	----	19.3	112.9	17.1	9	3.99	7.3
Oro	8220	----	----	----	----	4	19	12	0	100	24	13	30	15	25	----	30	15	----	50	25.9	177.4	14.6	13	3.76	6.4
Nebraska No. 60	6250	1	3	0	----	----	----	6	0	----	----	----	----	----	----	----	----	----	----	----	2.0	250.0	.8	5	3.69	6.2
Sherman	4430	----	----	----	----	----	----	----	----	----	30	23	30	----	28	23	30	----	20	30	26.8	225.2	11.9	8	3.57	6.0
Kharkof	1442	1	9	1	100	6	0	11	1	100	25	23	30	20	25	23	30	20	----	75	27.8	165.5	16.8	18	3.21	5.1

The correlation coefficient for average lodging at these stations and the breaking strength of straw at Denton was −0.729, which is highly significant.

These data clearly indicate that the very low coefficients for lodging and breaking strength given in table 5 are in part due to the paucity of data, especially with respect to lodging, and that when lodging data for a number of years or a number of stations are combined relatively high coefficients may be expected. This may explain the failure of some investigators to secure a significant correlation between lodging and the breaking strength of straw.

The fact that lodging is dependent on a number of factors, some at least varying from year to year, and that the correlation coefficients between lodging and breaking strength of straw increase with an increase in the number of years or number of stations included in the determinations suggests that the true relation between lodging and breaking strength of straw, as indicated by the correlation coefficients so far available, is underestimated. In other words, more extensive data than those now available, especially with reference to lodging, would probably provide even higher coefficients and consequently lead to placing greater confidence in breaking strength of straw as an adequate measure of tendency to lodge. Altogether, it would seem that there are sufficient data to support the belief that breaking-strength determinations can be used to predict lodging behavior in the field and consequently can be used in a breeding program to isolate strains resistant to lodging.

INTERANNUAL AND INTERSTATION CORRELATIONS, 1931–34

Interannual correlation coefficients for lodging and for breaking strength have been calculated for such varieties as were grown 2 or more years. The correlation coefficients are given in table 9. Only one of the coefficients for lodging, viz, for the period from 1932–34, is significant, whereas all those for breaking strength of straw are significant. In other words, so far as these data show there appears to be only a slight tendency for varieties to lodge the same from year to year as contrasted with a very strong tendency for them to have the same relative breaking strength of straw.

TABLE 9.—*Interannual correlation coefficients for lodging and breaking strength of straw*

Character correlated and year	Varieties	1932		1933		1934	
		Correlation coefficient	*P* value	Correlation coefficient	*P* value	Correlation coefficient	*P* value
Lodging:	*Number*						
1933	30	+0.013	0.95	----------	----------	----------	----------
1934	30	+.566	<.01	+0.050	0.79	----------	----------
Breaking strength of straw:							
1931	18	+.854	<.01	+.733	<.01	+0.632	<0.01
1932	65	----------	----------	+.756	<.01	+.816	<.01
1933	44	----------	----------	----------	----------	+.533	<.01

Interstation coefficients of breaking strength have also been calculated in some instances. Thus, for 15 varieties grown both at Denton, Tex., and Manhattan, Kans., during the 3-year period 1932–34, the

correlation coefficients for each individual year were 0.722, 0.346, and 0.58, respectively, and for the averages for all years, 0.787.

BREAKING STRENGTH OF STRAW AND WEIGHT PER UNIT LENGTH OF CULM

Breaking strength of straw, as may be noted in table 5, was correlated with height of plant and weight of grain per 100 heads and highly correlated with diameter of culm at the base of the plant, with weight of 100 culms, and with weight per unit length of culm at the base of the plant in each of the years in which these relations were studied. The chief interest lies in the possibility of substituting one of these determinations for breaking strength of straw as a measure of the tendency to lodge. The coefficients for breaking strength and weight per unit length of culm were especially high, viz, 0.956 and 0.911 for 1933 and 1934, respectively. The relation for 1934 is illustrated in figure 1.

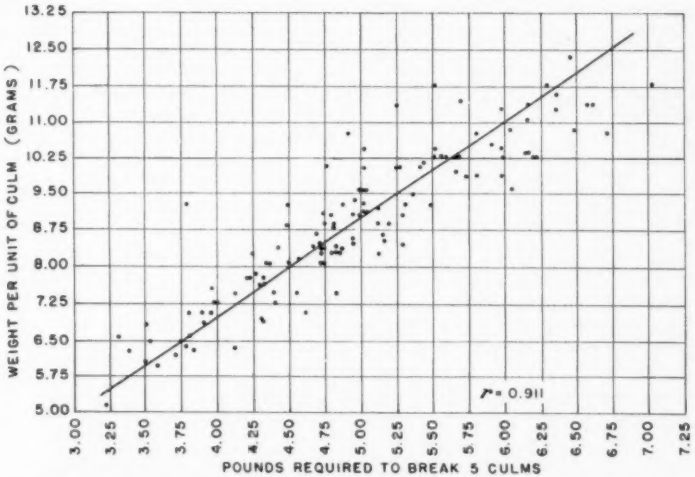

FIGURE 1.—Breaking strength of straw and weight per unit of culm at base of plant of 129 varieties of hard and soft winter wheats, Denton, Tex., 1934.

These coefficients are sufficiently high to suggest that weight per unit length of culm might safely be substituted for breaking-strength determinations. Such determinations would often be more convenient, as they do not involve the use of any special equipment, require less time, and in some respects may be expected to be more accurate. For one thing, the personal equation is involved to some extent in making breaking strength of straw determinations, as, for example, with respect to the speed with which the weight is lowered onto the straws. Errors of this sort are avoided in determinations of unit weight of culms.

As shown in table 5, there are no material differences in the coefficients between lodging and breaking strength of straw on the one hand and lodging and weight per unit length of culm on the other. In

no case are they statistically significant. For the data in table 6, the coefficient for lodging and weight per unit length of culm is −0.464, as compared with −0.422 for lodging and breaking strength. For the data in table 7, the corresponding coefficients are −0.625 and −0.575. For the data in table 8, the values are −0.666 and −0.729, respectively. For 36 varieties grown at Denton, in each of 2 years, the corresponding coefficients are −0.411 and −0.387.

The interannual coefficient for weight per unit length of culm in 1933 and 1934 is 0.586. This compares favorably with the corresponding coefficient (r=0.533) for breaking strength of straw for the same years (table 9). No data on weight per unit length of culm are available for other years or from other stations.

These results indicate that the weight per unit length of culm at the base of the plant is as good a measure of tendency to lodge as is breaking strength of straw. As already indicated, there are certain practical advantages in using the former.

SUMMARY

Varieties of winter wheat, varying in number from 18 to 129, were grown at the Texas Substation No. 6, Denton, Tex., in each of 4 years, and the relation of lodging to various plant characters, including breaking strength of straw and weight per unit length of culm, was studied. Data with respect to lodging for a number of the same varieties grown at Manhattan, Kans., New Brunswick, N. J., Pullman, Wash., Corvallis. Oreg., Logan and Newton, Utah, Urbana, Ill., Bozeman, Mont., Lincoln and North Platte, Nebr., Fort Collins and Akron, Colo., Waseca, Minn., and Woodward and Goodwell, Okla., were supplied by the agricultural experiment stations of the respective States, and the results were correlated with the breaking strength of straw and certain other characteristics of the same varieties as were grown at Denton.

Lodging was dependent on a number of factors that vary greatly from year to year, thus making it difficult to find any one index of lodging that may be considered completely reliable. A positive and significant though small correlation coefficient was recorded for lodging and length of lower internode and for lodging and date of maturity in one season only of the three in which these relations were studied; likewise, a positive and significant though small correlation coefficient was recorded for lodging and weight of grain per 100 heads in one season only of the two in which this relation was studied; and a small negative significant coefficient between lodging and weight per 100 culms and lodging and weight per unit length of culm in one season only of the two in which these relations were studied. All other coefficients, including lodging and breaking strength of straw, were small and were not statistically significant. Holding various factors constant by means of partial correlation coefficients raised the value of the coefficient for lodging and breaking strength of straw in some cases, but in no case did it reach the level of statistical significance.

When the average lodging for a number of years or a number of stations was correlated with breaking strength of straw for the same varieties as were grown at Denton, the coefficients were in all cases significant, and in most cases highly so. These results suggest that

the low coefficients sometimes secured for lodging and breaking strength of straw are due to the numerous factors that determine lodging in any single case, and they also suggest that failures to demonstrate a significant relation between lodging and breaking strength of straw are due in the main to lack of sufficient data with respect to lodging. In any event, the relation between breaking strength of straw and tendency to lodge appears to be such as to justify the use of the former in evaluating new varieties with respect to the tendency to lodge, particularly in a breeding program the purpose of which is to secure varieties resistant to lodging.

Relative breaking strength of straw is shown to be fairly constant from year to year, whereas lodging is not, from which it would appear that determinations of breaking strength for a single season are a more reliable index of tendency to lodging than is a record of lodging itself for a single season.

Correlation coefficients between lodging and weight per unit length of culm taken near the base of the plants were as high as, or higher than, those between lodging and breaking strength of straw. Determinations of the former require no special equipment, are more quickly and easily made, and in some respects are believed to be more accurate. It is therefore suggested that weight per unit length of culm near the base may be used to advantage, instead of breaking strength of straw, as an index of lodging.

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EFFECT OF CARBON DIOXIDE STORAGE ON BARTLETT PEARS UNDER SIMULATED TRANSIT CONDITIONS[1]

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INTRODUCTION

The Bartlett is by far the most popular pear variety grown in the United States. Its commercial production is confined largely to the three Pacific Coast States, where approximately 80 percent of the total pear acreage is planted to this variety (*16*).[2]

The transportation of a large portion of this Bartlett pear tonnage to eastern markets should be accomplished with little loss of storage capacity and dessert quality. This variety is stored and transported best at temperatures of 29° to 30° F. (*17*), but during transportation and market distribution it is difficult to maintain temperatures below 40°, and temperatures much higher than this are likely to prevail. Even with precooled fruit it is not possible at present to keep the load cool enough in all parts of a refrigerator car to prevent considerable ripening. When subjected to temperatures between 40° and 50°, Bartlett pears soon show a yellow ground color, ripen rapidly, and break down at the core. Consequently they frequently undergo these changes before reaching the consumer.

The storage life of many fruits and vegetables may be considerably extended by increasing the concentration of carbon dioxide gas in the storage atmosphere (*1*, *14*). The data presented in this paper are based on a study of the storage and ripening behavior of Bartlett pears when refrigeration has been supplemented by the use of carbon dioxide gas. The tolerance of the fruit for this gas has been studied by varying the concentration, temperature, and period of exposure. Differences in degree of ripeness or firmness of the fruit under various storage practices have been measured in terms of soluble pectin. The experimental work here reported was done at Wenatchee, Wash., and represents one phase of a general investigation of the handling and storage of the Bartlett pear that is being carried on at this station (*6*, *7*, *9*, *10*).

REVIEW OF LITERATURE

No attempt will be made to present a thorough discussion of the rapidly increasing literature dealing with gas storage of fruits and vegetables. For such a discussion reference should be made to the reviews of Brooks et al. (*3*), Thornton (*25*), and Eaves (*5*).

Low-temperature disorders sometimes become limiting factors in the successful storage of apples at 32° F. (*14*). Kidd and West (*12*, *13*) have shown that in such instances satisfactory storage life can be preserved at higher temperatures by reducing the oxygen and increasing the carbon dioxide content of the storage air. The concentration

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[2] Reference is made by number (italic) to Literature Cited, p. 134.

of these two gases in the storage air differed according to the variety of fruit under observation. For maximum storage life at 40°, Bramley Seedling required 11 to 13 percent of oxygen and 8 to 10 percent of carbon dioxide; Cox Orange Pippin, on the other hand responded best to atmospheres carrying 2.5 percent of oxygen and 5 of carbon dioxide.

Trout (*26*) studied the storage behavior of pears in atmospheres containing various concentrations of nitrogen and carbon dioxide at storage temperatures of 37.4°, 50.0°, and 64.4° F. At the two higher temperatures he obtained no beneficial results as compared with controls held in air. At 37.4° he was able to store pears successfully for 21 days in an oxygen-free atmosphere containing less than 10 percent of carbon dioxide. These pears ripened 6 weeks after being placed in storage as compared with 4 weeks for controls held in air; i. e., their storage life was prolonged by 50 percent. Kidd et al. (*15*) studied the storage behavior of Comice pears at 37.4° in artificial atmospheres ranging from 0 to 20 percent in carbon dioxide content and from 21 to 0.2 percent in oxygen content. These authors found that subnormal oxygen over a range of 21 to 2 percent produced only a slight retardation of ripening in atmospheres devoid of carbon dioxide and that "the higher the oxygen content the more sweet the ripened pear." A marked depression in the rate of ripening occurred when the oxygen level was lowered to 0.2 percent. Carbon dioxide in the presence of oxygen above 2 percent greatly retarded ripening; the degree of retardation varied with the concentration of carbon dioxide present. After storage in air at 37.4° for 84 days, Comice pears ripened in 8 days when removed to 50°; comparable fruit held in 10 percent of carbon dioxide and 6 percent of oxygen for a similar period ripened in 20 days, while that stored in 20 percent carbon dioxide required 27 days to ripen properly.

Working with Bartlett pears, Thornton (*25, p. 229*) obtained little benefit from the use of increased concentrations of carbon dioxide. He states:

> Unlike the Anjou variety, the freshly harvested Bartlett pear was greatly injured by storage for 7 days in 28 percent of carbon dioxide at all temperatures. The Bartlett pears in 10 percent of carbon dioxide were similar to the controls in color and firmness, but they were less astringent in flavor.

It is difficult to reconcile Thornton's results with those of other workers (*3, 15*) and with those obtained in the present investigation.

Brooks, Cooley, and Fisher (*2*) have shown that the carbon dioxide tolerance of Grimes Golden apples increased with a reduction in storage temperature. Flavor was unaltered by storage of the fruit in 100 percent of carbon dioxide for 6 days at 50° F., whereas injury resulted after 2 days at 86°. Magness and Diehl (*19*) obtained no appreciable effect upon the flavor of Winesap and Delicious apples by storing them for 10 days at 71.6° in 20 percent of oxygen and 5 to 10 percent of carbon dioxide; the rate of softening, however, was markedly retarded. Concentrations of 20-percent carbon dioxide or higher produced fermentative "off flavors." Thornton (*25*) has reported Delicious apples as being twice as tolerant as McIntosh to abnormal concentrations of carbon dioxide. No injury was observed in Delicious held for 7 days in 83-percent carbon dioxide at 32° or in 50 percent at 50°; McIntosh under similar conditions withstood carbon dioxide concentrations of 48 and 25 percent, respectively. Overholser

(*23*) found that 20 to 25 percent of carbon dioxide prevented softening of Fuerte avocados at 45° and no objectionable flavors were produced during or after storage. Fruit stored in concentrations of 4 to 5 percent of this gas at 45° could be held a month longer than the control.

MATERIAL AND METHODS

Bartlett pear fruits were selected for uniformity of size and maturity from typical, vigorous, 27-year-old trees growing under comparable orchard conditions. The fruit was harvested at optimum maturity, as indicated for each season, washed in cold 1-percent hydrochloric acid, wrapped in oiled paper, packed in standard 44-pound pear boxes, and placed immediately under experimental storage conditions. Fruit destined for carbon dioxide storage was placed in galvanized-metal chambers, 26 cubic feet in capacity, and each was fitted with a flanged edge and a water seal in which the cover rested. Copper tubes in the cover facilitated transfer and measurement of the gases. A small electric fan mounted inside the cabinets circulated the enclosed atmosphere, prevented stratification, and facilitated carbon-dioxide measurements. The carbon dioxide was obtained from cylinders of compressed gas. Atmospheric measurements of the gas were made with an Orsat-Fischer gas apparatus. The carbon-dioxide concentrations did not vary more than 2 percent during the course of any experiment. No attempt was made to depress the concentration of oxygen below that which would normally follow replacement during the addition of specified amounts of carbon dioxide. The maintenance of still lower oxygen concentrations appears to be impracticable under present commercial transit conditions; furthermore, as shown by Kidd et al. (*15*), the beneficial results therefrom would be of little importance.

Fruit destined for ripening studies was removed to 65° F. and a relative humidity of approximately 85 percent. Pressure tests of firmness were made on the pared flesh of 10 representative fruits by means of the $\frac{5}{16}$-inch plunger of a pressure tester developed by the United States Department of Agriculture. Soluble-pectin determinations were made on 100 g of juice after clarification and filtration through filter-cell. The method of precipitation and measurement of soluble pectin was essentially that of Carré and Haynes (*4*). Preliminary trials, in which 100 g of tissue were used as compared with 100 g of juice, substantiated the results reported by Haller (*8*), namely, that similar amounts of soluble pectin were obtained irrespective of the two sampling techniques used.

RESULTS FOR 1934

Preliminary work, involving a study of the storage quality and ripening behavior of Bartlett pears as influenced by various handling and storage practices, was begun in 1934. The pears were harvested on July 26 at 15.6 pounds' pressure. Certain lots of fruit were subjected to conditions similar to those the fruit would have encountered in transit (45° F. for 10 days), while others were given a short precooling or a short exposure to carbon dioxide prior to storage. Certain lots were held at a higher temperature (65°) in carbon dioxide before they were stored at 32°. Fruit from all these treatments was compared with fruit that had been stored immediately in air at

32°. Pressure test, condition, and dessert quality of the various lots were compared at intervals during storage at 32° and during subsequent ripening at 65°. Pertinent data are presented in table 1.

TABLE 1.—*Condition and dessert quality of Bartlett pears in 1934 as influenced by various handling practices at harvest and by periods of storage at 32° F.*

Handling practice	Storage at 32° F.	Pressure test	Color and condition	Ripening period at 65° F.	Surface scald or core break-down	Dessert quality
	Days	*Lb.*		*Days*		
Immediate storage at 32° F.	0	15.5	Dark harvest green, excellent.	11	None	Excellent.
	38	15.0	Dark green, excellent	5	do	Do.
	79	14.4	Light green, some yellow	5	do	Good.
45° F. for 10 days, then 32°.	0	9.7	Light green, very good	4	do	Excellent.
	28	4.4	Yellow, firm, hard ripe	4	do	Good.
	60	3.3	Yellow, surface scald, poor.	5	Scald, core break-down.	Poor.
Precooled at 32° F. for 24 hours, 45° for 10 days, then 32°.	0	14.1	Green, very good	4	None	Excellent.
	28	7.0	Light green, some yellow	4	do	Very good.
	69	6.8	Full yellow, some scald	5	Scald, core break-down.	Poor.
65° F. for 24 hours in 35 percent CO_2, 45° for 10 days, then 32°.	0	10.6	Light green, very good	4	None	Excellent.
	28	5.7	Yellow, firm, hard ripe	4	do	Good.
	69	4.5	Full yellow, scald, poor	5	Scald, core break-down.	Poor.
65° F. for 10 days in 20 percent CO_2, then 32°.	0	15.5	Dark green, excellent	6	None	Excellent.
	28	15.2	Light green, very good	4	do	Good.
	69	15.5	Full yellow, no scald	5	do	Fair to poor.
65° F. for 10 days (check).	0	.....	Full yellow, eating ripe	0	do	Excellent.

The dessert quality of all lots, irrespective of handling practice was excellent when the fruit was ripened immediately after treatment. This was still true of the different lots after a storage period of 28 days at 32° F. Differences in potential storage life were great at this time, however, as shown in table 1. Transit temperatures of 45° for 10 days, even when supplemented by precooling or pregassing for 24 hours, greatly stimulated the ripening processes; precooling, however, was more beneficial than gas treatment. The potential storage life of these lots held at 45° for 10 days was decreased over 60 percent as compared to similar fruit stored immediately at 32°.

Pears held in air for 10 days at 65° F. following harvest were "eating" ripe. Those held in 20-percent carbon dioxide under similar conditions were dark green and appeared comparable in color and firmness to those stored immediately at 32°. Subsequent softening of the gas-treated fruit was retarded by air storage at 32°, as is shown by the pressure test after 28 days' storage at this temperature. Dessert quality and flavor of the ripened gas-stored fruit was good after 28 days at 32°; after 69 days, although no scald or core breakdown had occurred, the flavor was definitely impaired.

Fruit held at 45° F. for 10 days at harvest and stored for 69 days at 32° became overripe, badly scalded, and broken down at the core even in cold storage; senescence was decidedly more advanced than in comparable lots held for 10 days at 65° in 20 percent of carbon dioxide.

RESULTS FOR 1935

Storage investigations were undertaken during 1935 to determine the supplementary value of carbon dioxide in the handling of Bartlett pears under conditions similar to those the fruit would have encountered in transit. Two lots of pears were held for 10 days in 20 per cent of the gas at temperatures of 45° and 65° F., respectively. A control lot for the fruit held at each of the above-mentioned temperatures and one lot that was stored immediately at 32° were used for comparative observations. The fruit was harvested on August 20 at 17.3 pounds' pressure and placed under experimental storage conditions within 4 hours from the time of picking. After 10 days at the higher temperatures, it was placed at 32° and withdrawals were made at irregular intervals for studies on ripening, pressure test, and dessert quality. The data pertaining to these observations are presented in table 2.

TABLE 2.—*Storage and ripening capacity of Bartlett pears in 1935 as influenced by various handling practices at harvest and by periods of storage at 32° F.*

Handling practice	Storage at 32° F.	Pressure test	Color and condition	Ripening period at 65° F.	Surface scald or core break-down	Dessert quality	Additional period of edibility
	Days	*Lbs.*		*Days*			*Days*
Immediate storage at 32° F.	10	18.1	Dark harvest green, excellent.	8	None	Excellent	6
	50	17.1	Dark green, excellent	5	do	do	4
	72	16.3	Light green, slight yellow, very good.	5	do	Very good	2
	102	16.0	Very light green, much yellow, fair	6	Core breakdown, no scald.	Poor	0
15° F. for 10 days, then 32°	0	17.0	Light green, very good	6	None	Very good	4
	40	14.2	Almost full yellow, fair	5	Core breakdown, no scald.	Poor	0
	62	13.4	Full yellow, scald, and core break-down.				
15° F. for 10 days in 20 percent CO_2, then 32°	0	17.1	Dark harvest green, excellent.	8	None	Excellent	6
	40	16.3	Green, no yellow, very good.	5	do	Very good	2
	62	16.5	Light green, some yellow, good.	5	do	do	2
	92	15.4	Similar to fruit given immediate storage at 32°.	6	Core breakdown, no scald.	Poor	0
65° F. for 10 days in 20 percent CO_2, then 32°.	0	17.0	Dark green, excellent	8	None	Excellent	6
	40	16.3	Similar to lots delayed at 45° for 10 days.	5	do	Fair, slight alcoholic taste.	1
	62	16.6	Full yellow, no scald or core break-down.	5	do	Poor, off flavor	0
65° F. for 10 days (check).	0		Full yellow, eating ripe	0	do	Excellent	8

Here again "transit" conditions (45° F. for 10 days) greatly lowered the potential storage life of the fruit. Carbon dioxide storage at 65° for 10 days was decidedly more beneficial than air storage at 45°. Fruit held for 10 days in 20 percent of carbon dioxide at 65° was in fair condition, free from scald or core break-down and of fairly edible quality (slightly alcoholic taste) after 40 days' storage at 32°, while that delayed for 10 days at 45° in air was of poor dessert quality and showed core break-down but no surface scald after a similar period of storage at 32°.

The addition of 20 percent of carbon dioxide to the storage atmosphere during delay at 45° F. so retarded ripening and the development of yellow ground color that fruit treated in this manner compared favorably in dessert quality and potential storage life with similar fruit stored immediately at 32°. The efficiency of carbon dioxide storage varied with the temperature. Fruit stored in this gas at 45° was decidedly superior to similar lots stored in gas at 65°. These differences were reflected in the color and condition of the fruit in subsequent cold storage, as shown in table 2. Carbon dioxide storage at 65°, however, was preferable to air storage at 45°.

RESULTS FOR 1936

GAS STORAGE EXPERIMENTS

During 1936 more detailed consideration was given to certain problems associated with carbon dioxide storage of Bartlett pears. Fruit for these studies was harvested August 13 and gave a pressure test of 17.6 pounds; it was placed immediately under experimental storage conditions. It should be recognized that the greatest practical benefits of gas treatment depend upon its use at storage temperatures higher than 32° F. Since transit temperatures for pears approximate 45° more nearly than 32°, the higher temperature received major consideration in the following experiments. For reasons more technical than practical, gas-storage studies were also made at 65° in 20 percent gas for 10 to 30 days. The tolerance of Bartlett pears to carbon dioxide at 45° was determined by varying the concentration of gas from 10 to 35 percent and the time from 10 to 30 days. Check lots of fruit were air-stored immediately at 32° and after various periods of delay at 45°.

All the delayed lots of fruit were stored in air at 32° F. for further comparison of their potential storage life and dessert quality. Withdrawals were made at irregular intervals and the fruit was ripened at 65°. Data relative to the firmness, color, and condition of the various lots immediately after delayed storage and before subsequent storage at 32° are presented in table 3.

TABLE 3.—*Color and condition of Bartlett pears in 1936 as influenced by various handling practices at harvest and prior to storage at 32° F.*

Handling practice	Pressure test	Color and condition
	Pounds	
Immediate storage at 32° F.	17.6	Dark harvest green, excellent.
45° F. for 10 days	17.0	Dark green, excellent.
45° F. for 15 days	7.1	Medium to light green, some softening.
45° F. for 20 days	3.7	Greenish yellow to full yellow, hard ripe.
45° F. for 30 days		Full yellow, poor condition, severe scald, no breakdown.
45° F. for 10 days in 10 percent CO_2	18.0	Dark harvest green, excellent.
45° F. for 15 days in 10 percent CO_2	17.5	Medium green, excellent.
45° F. for 20 days in 10 percent CO_2	15.6	Light green, slight yellow, good.
45° F. for 30 days in 10 percent CO_2	16.0	Do.
45° F. for 10 days in 20 percent CO_2	18.2	Dark harvest green, excellent.
45° F. for 15 days in 20 percent CO_2	17.5	Do.
45° F. for 20 days in 20 percent CO_2	16.5	Do.
45° F. for 30 days in 20 percent CO_2	16.8	Light green, good.
45° F. for 10 days in 35 percent CO_2	17.8	Dark harvest green, excellent.
45° F. for 15 days in 35 percent CO_2	17.8	Do.
45° F. for 20 days in 35 percent CO_2	17.6	Do.
45° F. for 30 days in 35 percent CO_2	17.5	Do.
65° F. for 10 days in 20 percent CO_2	18.0	Dark harvest green, good condition, slightly tough.
65° F. for 15 days in 20 percent CO_2	12.0	Light green to faint yellow, tough texture.
65° F. for 20 days in 20 percent CO_2	5.1	Full yellow, hard ripe.
65° F. for 30 days in 20 percent CO_2		Full yellow, soft, stale alcoholic, severe beak-down.
65° F. for 10 days (check)		Full yellow, prime dessert quality.

The data in this table indicate the degree of change that may be anticipated during the movement of fruit to market under different handling practices. The rate of ripening in air storage was very rapid at 45° F., but was greatly retarded by the addition of 10 percent of carbon dioxide to the storage air. At the end of 20 days the pressure test for the fruit stored in air was 3.7 pounds, and for that stored in 10 percent of carbon dioxide 15.6 pounds. During storage at 45° for periods of 15 days or longer a greater decrease in the rate of ripening was brought about by the addition of 10 percent of carbon dioxide to the storage air than by increasing the concentration of the gas from 10 percent to 20 percent or from 20 percent to 35 percent. The change in color of the fruit during storage at 45° was markedly retarded by increasing the concentration of gas to 20 percent; little additional retardation of change in color was found when the concentration was increased to 35 percent.

Fruit became eating ripe after 10 days in air storage at 65° F. Comparable lots of fruit held in 20 percent carbon dioxide for a similar period were firm, dark green, and, so far as could be determined, compared favorably with those stored immediately at 32°. Fruit held in gas for 20 days under similar conditions, however, was eating ripe and of good dessert quality. When the period of gas storage at 65° was extended beyond 20 days, dessert quality was greatly impaired. Accumulation of fermentative "off flavors" was probably the result of anaerobic respiration.

After having received the various preliminary treatments at harvest as shown in table 3, the pears were placed in storage at 32° F. Observations on the condition and potential storage life of these fruits at this temperature were made at irregular intervals thereafter. These data are summarized in table 4.

Fruit stored immediately at 32° F. could be held for 80 days; lots receiving delayed storage at 45° for 10 days without gas were firm ripe in 38 days, while those held for 15 days under similar conditions gave evidence of considerable ripening after 5 days at 32°. Carbon dioxide, even in the smaller amount of 10 percent, greatly increased the potential storage life of Bartlett pears. This conclusion is substantiated by the data under the heading "Color and condition" in table 4.

When fruit was delayed in 20-percent and 35-percent concentrations of gas at 45° F. transit temperature, it had a subsequent keeping quality equal to that of fruit stored immediately at 32°; in some instances (35-percent gas for 30 days) it showed less change in color after prolonged storage at 32° than did similar fruit held continuously at the latter temperature.

Bartlett pears softened very rapidly when held in air at 65° F.; they were eating ripe after a period of 10 days. A decided retardation in the rate of ripening occurred at this temperature when 20 percent of carbon dioxide was added to the storage atmosphere. Fruit after 10 days in such carbon dioxide storage was harvest green in color and could be held for an additional period of 10 days at 32° without impairment of dessert quality. Changes associated with ripening increased, however, even in gas storage, when the period of delay was longer than 10 days at 65°. Surface scald and core break-down resulted when gas storage at 65° was extended to 30 days.

Air storage at 45° F. was also detrimental to the potential storage life of pears. Under these conditions, changes in color and firmness

were greater than during gas storage at 65°. Surface scald and core break-down were apparent when the fruit was delayed at the transit temperature of 45° for 15 days or longer. Even after a 10-day period of delay, the potential storage life at 32° was reduced to less than 38 days. The susceptibility of pears to surface scald and core break-down was greater in air storage at 45° than in gas storage at 65°.

TABLE 4.—*Color and condition of Bartlett pears in 1936 as influenced by various handling practices at harvest and by periods of storage at 32° F.*

Handling practice	Storage at 32° F.	Pressure test	Color and condition
	Days	*Pounds*	
Immediate storage at 32° F.	20	17.5	Dark green, excellent.
	48	16.7	Dark green, no yellow color, good appearance.
	80	17.1	Light green, some yellow ground color, good.
45° F. for 10 days, then 32°	10	15.0	Light green, no yellow color, very good.
	38	8.7	Full yellow color, firm, hard ripe.
	70	7.2	Full yellow color, hard ripe, severe surface scald.
45° F. for 15 days, then 32°	5	5.2	Light green, considerable yellow ground color.
	33	.....	Full yellow, severe surface scald and core break-down.
45° F. for 20 days, then 32°	28	.....	Do.
45° F. for 30 days, then 32°	18	.....	Do.
45° F. for 10 days in 10 percent CO_2, then 32°	10	15.4	Green, no yellow color, very good.
	38	15.6	Do.
	70	17.0	Light green, some yellow, good.
45° F. for 15 days in 10 percent CO_2, then 32°	5	15.2	Light green, faint yellow, very good.
	33	15.5	Light green, faint yellow, good.
	65	16.0	Full yellow color, fair.
45° F. for 20 days in 10 percent CO_2, then 32°	28	15.0	Full yellow color, fair, no scald.
	60	11.2	Full yellow color, some softening, no scald.
45° F. for 30 days in 10 percent CO_2, then 32°	18	12.0	Do.
	50	8.7	Full yellow color, hard ripe, no scald.
45° F. for 10 days in 20 percent CO_2, then 32°	10	16.0	Dark harvest green, excellent.
	38	16.8	Dark green, excellent.
	70	17.2	Light green, better than fruit given immediate storage at 32° F.
45° F. for 15 days in 20 percent CO_2, then 32°	5	15.5	Dark harvest green, excellent.
	33	16.0	Dark green, like fruit given immediate storage at 32° F.
	65	18.0	Light green, like fruit given immediate storage at 32° F.
45° F. for 20 days in 20 percent CO_2, then 32°	28	16.5	Green, no yellow color, very good.
	60	16.8	Light green, like fruit given immediate storage at 32° F.
45° F. for 30 days in 20 percent CO_2, then 32°	18	16.0	Light green, some yellow color, good.
	50	17.0	Full yellow, fair condition, no scald.
45° F. for 10 days in 35 percent CO_2, then 32°	10	16.0	Dark harvest green, excellent.
	38	16.7	Darker green than fruit given immediate storage at 32° F.
	70	17.7	Dark green, very good.
45° F. for 15 days in 35 percent CO_2, then 32°	5	16.1	Dark harvest green, excellent.
	33	16.8	Darker green than fruit given immediate storage at 32° F.
	65	17.0	Dark green, very good.
45° F. for 20 days in 35 percent CO_2, then 32°	28	16.0	Darker green than fruit given immediate storage at 32° F.
	60	16.7	Dark green, very good.
45° F. for 30 days in 35 percent CO_2, then 32°	18	16.4	Dark green, like fruit given immediate storage at 32° F.
	50	17.0	Dark green, very good.
65° F. for 10 days in 20 percent CO_2, then 32°	10	16.8	Light green, no yellow color, good.
	38	15.0	Considerable yellow color, fair.
	70	14.4	Almost full yellow, some softening, no scald.
65° F. for 15 days in 20 percent CO_2, then 32°	5	11.3	Considerable yellow color, some softening.
	33	9.5	Full yellow, marked softening, no scald.
65° F. for 20 days in 20 percent CO_2, then 32°	28	4.0	Full yellow color, hard ripe, no scald nor break-down.
65° F. for 30 days in 20 percent CO_2, then 32°	18	.....	Full yellow, soft mealy, surface scald and break-down.
65° F. for 10 days (check)	0	.....	Full yellow color, prime dessert quality.

The color, condition, and firmness of the unripened fruit as influenced by various handling practices and periods of storage have been presented in some detail in the preceding discussion of the results for 1936. Ripening studies were also made on comparable fruit held at

65° F. after storage at 32°. Data pertaining to differences in ripening capacity and dessert quality, observed at intervals, are shown in table 5.

Bartlett pears stored immediately at 32° F. could be ripened with very good dessert quality after 80 days' storage. No surface scald or core break-down developed. The additional period of edibility of this fruit after acquiring prime dessert quality decreased, however, with prolonged storage, from 7 to 2 days. Fruit held at 45° without carbon dioxide for longer than 15 days was so advanced in maturity as to be unfit for further storage at 32°; even that delayed for 10 days under these conditions was worthless after 38 days at the lower temperature.

TABLE 5.—*Ripening of Bartlett pears in 1936 as influenced by various handling practices at harvest and by periods of storage at 32° F.*

Handling practice	Storage at 32° F.	Ripening period at 65° F.	Surface scald or core break-down when ripened	Dessert quality	Additional period of edibility
	Days	*Days*			*Days*
Immediate storage at 32° F.	20	7	None	Excellent	7
	48	5	do	do	4
	80	5	do	Very good	2
45° F. for 10 days, then 32°	10	4	do	do	3
	38	4	Core break-down	Poor	0
45° F. for 15 days, then 32°	5	4	None	Fair, slightly mealy	1
45° F. for 20 days, then 32°	0	3	do	Fair, mealy	2
45° F. for 10 days in 10 percent CO_2, then 32°	10	6	do	Excellent	8
	38	5	do	Very good	2
	70	4	Slight core break-down	Poor to fair	0
45° F. for 15 days in 10 percent CO_2, then 32°	5	5	None	Excellent	8
	33	5	Slight core break-down	Poor to fair	0
	65	5	Core break-down	Poor	0
45° F. for 20 days in 10 percent CO_2, then 32°	0	5	None	Excellent	9
	28	5	Slight core break-down	Poor	0
	60	5	Severe core break-down	do	0
45° F. for 30 days in 10 percent CO_2, then 32°	18	5	Slight core break-down	do	0
	50	5	Severe core break-down	do	0
45° F. for 10 days in 20 percent CO_2, then 32°	10	7	None	Excellent	7
	38	5	do	Very good	4
	70	5	do	Good	1
45° F. for 15 days in 20 percent CO_2, then 32°	5	7	do	Excellent	7
	33	5	do	Very good	2
	65	5	do	Good	1
45° F. for 20 days in 20 percent CO_2, then 32°	0	6	do	Excellent	8
	28	5	do	Very good	2
	60	5	do	Poor, tough	1
45° F. for 30 days in 20 percent CO_2, then 32°	18	5	do	Very good	2
	50	5	Core break-down	Poor	0
45° F. for 10 days in 35 percent CO_2, then 32°	10	7	None	Excellent	3
	38	5	do	Very good	3
	70	5	do	Good, tart	2
45° F. for 15 days in 35 percent CO_2, then 32°	5	7	do	Excellent	3
	33	5	do	Very good	1
	65	5	do	Good	1
45° F. for 20 days in 35 percent CO_2, then 32°	0	7	do	Excellent	3
	28	6	do	Very good	1
	60	5	do	Good	1
45° F. for 30 days in 35 percent CO_2, then 32°	18	6	do	Very good	1
	50	5	do	Good	1
65° F. for 10 days in 20 percent CO_2, then 32°	10	5	do	Excellent	3
	38	5	do	Fair, slightly alcoholic	0
	70	5	Core break-down	Poor	0
65° F. for 15 days in 20 percent CO_2, then 32°	5	5	None	Very good	1
	33	5	Core break-down	Poor	0
65° F for 20 days in 20 percent CO_2, then 32°	0	5	None	Very good	1
	33	5	Core break-down	Poor	0
65° F. for 30 days in 20 percent CO_2 then 32°	0	0	Severe core break-down	Poor, stale, alcoholic	0
65° F. for 10 days (check)	0	10	None	Excellent	8

The addition of 10 percent of carbon dioxide to the atmosphere during delay at 45° F. prolonged the storage life at 32°. This fact is shown in table 5 by a comparison of fruit so treated with the air-stored

lot after 38 days' storage. Carbon dioxide at a concentration of 10 percent during periods of delay of 15 and 20 days extended the period of edibility considerably in lots which were ripened either immediately after storage or 5 days thereafter. During periods of delay at 45° for more than 10 days, carbon dioxide at this concentration afforded little or no protection against core break-down in Bartlett pears destined for prolonged storage.

The use of carbon dioxide in higher concentrations of 20 and 35 percent, during delay at 45° F., added materially to the period of time during which Bartlett pears could be successfully stored and ripened. In dessert quality, flavor, and freedom from surface scald and core break-down, such fruit compared favorably with lots stored immediately at 32°. No significant differences in storage or ripening capacity were detected between lots receiving 20 percent or 35 percent of the gas during delay. The only apparent difference was one of color; fruit in 35 percent gas was a shade greener during storage. Evidently 20 percent of carbon dioxide was sufficient to effect the maximum retardation of the ripening processes at 45°. Concentrations up to 35 percent or higher constitute a wide range that may be tolerated without injurious results.

Bartlett pears delayed at 65° F. in 20 percent carbon dioxide for more than 10 days were unsuited for storage at low temperatures. However, fruit could be held for 20 days in gas at 65° and then ripened immediately and still retain good dessert quality. Core break-down and a disagreeable, stale, sour, alcoholic taste usually accompanied prolonged gas storage at 65°. The fruit subjected to gas for 10 days at 65° could be held for an additional period of 10 days at 32° and ripened with no impairment of flavor; dessert quality, however, was impaired after storage for 38 days.

CHANGES IN PECTIN CONTENT OF BARTLETT PEARS

Decided changes in physical condition occur in Bartlett pears as they ripen to prime dessert quality; the most pronounced of these is the change in firmness of the flesh. This firmness, as recorded by the pressure test, may decrease from 15 to 18 pounds in unripened green fruit to 1 or 2 pounds in fruit that is fully ripened. Insoluble pectic material in cellular structure is often associated with maintenance of tissue rigidity. Hydrolysis of insoluble protopectin to soluble forms may be intimately associated with the softening of the fruit during normal ripening. In order to study this relationship Bartlett pears were harvested at optimum maturity and stored immediately at 32° F. for 38 days. During subsequent ripening at 65°, analyses for soluble pectin were made; the results are presented in table 6 and figure 1.

TABLE 6.—*Changes in soluble pectin content of Bartlett pears during ripening at 65° F. subsequent to storage at 32° F. for 38 days*

Ripened at 65° F. (days)	Soluble pectin	Color and condition of ripening fruit
	Percent	
0	0.025	Dark green, excellent storage condition.
2	.125	Light green, very firm.
4	.815	Full yellow, firm ripe.
8	.460	Overripe, no tissue discoloration.
11	.280	Overripe, slight core break-down.

That there is a significant correlation between degree of ripeness and production of soluble pectin is evident from table 6, which shows that the maximum formation of soluble pectin occurred before the fruit became overripe. The decrease of soluble pectin during senescence was probably caused by the more rapid hydrolysis of soluble pectin to pectic acid than of protopectin to soluble pectin. The speed at which changes in soluble pectin occur may be noted from figure 1. The soluble pectin increased almost sixfold in 2 days and reached a maximum in 4 days, when the fruit was firm ripe. Soluble pectin then decreased rapidly prior to the appearance of core break-down.

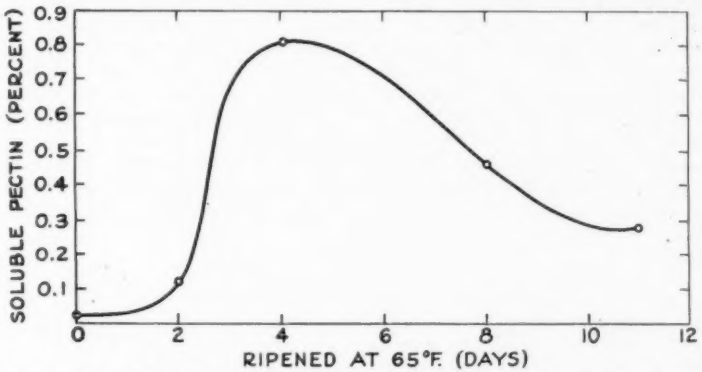

FIGURE 1.—Changes in soluble pectin content of Bartlett pears during ripening subsequent to storage at 32° F. for 38 days.

Since a significant correlation was found between degree of maturity and content of soluble pectin in Bartlett pears and since carbon dioxide has been shown to retard ripening, it became of physiological interest to study the effect of carbon dioxide storage on protopectin hydrolysis. Should gas storage depress the formation of soluble pectin, it would offer a possible explanation for the apparent efficiency of carbon dioxide in retarding the ripening of Bartlett pears. Data bearing on this subject are given in table 7.

The formation of soluble pectin was arrested in fruit that was stored immediately at 32° F. and held at this temperature for 13 or for 48 days. Ripening processes also were greatly retarded under similar circumstances.

TABLE 7.—*Soluble pectin content of Bartlett pears as influenced by various handling practices and by periods of storage at 32° F.*

Handling practice	Storage at 32° F.	Soluble pectin
	Days	*Percent*
Immediate storage at 32° F. (check)	13	0.0230
45° F. for 13 days in 20 percent CO_2	0	.0240
45° F. for 13 days	0	.3100
Immediate storage at 32° F (check)	48	.0250
45° F. for 13 days	33	.4720
45° F. for 13 days in 10 percent CO_2	33	.1000
45° F. for 13 days in 20 percent CO_2	33	.0325
45° F. for 13 days in 35 percent CO_2	33	.0287

Ripening progressed during delayed storage at 45° F. for 13 days and soluble pectin increased more than twelvefold to a concentration comparable with that in fruit ripened at 65° for several days (table 6). The soluble pectin in lots receiving such delayed storage increased about 52 percent when stored at 32° for 33 days. These facts substantiate practical storage observations that low temperature will not stop ripening in pears when once it has begun.

Determinations of soluble pectin were not made on the gas-stored lots immediately after treatment, but on similar lots after 33 days' storage at 32° F. From the data in table 7 it may be concluded that carbon dioxide definitely retarded ripening by depressing the hydrolytic (enzymatic) processes responsible for the formation of soluble pectin. The degree of retardation depended to some extent on the concentration of carbon dioxide. Gas concentrations of 20 and 35 percent gave soluble-pectin values comparable to those in fruit stored immediately at 32°. Data previously presented also indicate that these lots were similar in storage behavior and ripening capacity. It appears from the data presented in tables 6 and 7 that the degree of ripening and the potential storage life in Bartlett pears may be measured or predicted by evaluating the soluble-pectin content of the juice.

DISCUSSION

It should be recognized that the authors do not mean to recommend supplanting air storage of Bartlett pears at 30° to 31° F. with storage in artificial atmospheres of carbon dioxide at higher temperatures. The former practice should remain the accepted one whenever feasible. However, when sufficiently low temperatures are not available, as during transportation, congestion during harvest, or because of lack of refrigerated space, gas storage could be employed to great advantage as a supplement to low temperature in lengthening the storage life of Bartlett pears.

Magness and Ballard (*18*) and Magness et al. (*20*) have shown experimentally, and fruit auctions have evaluated commercially, a difference in the shipping and storage quality of Bartlett pears grown in various producing areas. Fruit from certain districts responds more readily to temperature stimulus than that from other districts, i. e., it will ripen more rapidly during a given length of time and in transportation to eastern markets will be in a more advanced state of ripeness on arrival. The potential storage life of this fruit could be greatly prolonged by the addition of carbon dioxide to the air in the car during transit.

From the viewpoint of commercial adaptability, it is fortunate that there is such a margin of safety in concentrations of CO_2 when Bartlett pears are exposed to an artificial atmosphere of this gas. Brooks et al. (*3*), using pony refrigerators, have determined the effective concentrations of this gas for storing Bartlett pears during periods of exposure up to 3 days at temperatures of 45° to 52° F. For Seckel pears these authors report no impairment of flavor or other evident injury after storage for 11 days at 66° in 50 percent of carbon dioxide, or for 17 days at 48° in a similar atmosphere. Thornton (*25*) has reported inability to successfully store Bartlett pears, obtained from a local wholesale dealer, for 7 days in 28 percent of carbon dioxide at temperatures of 32° to 50°. Because of the source of his material, however, it seems probable that the fruit might have been rather ripe

before it was placed in gas storage. If this were true it would explain the failure of Thornton's results to substantiate those of Brooks et al. (*3*), of Kidd, West, and Trout (*15*), and of the present authors, for when ripening once begins in pears it is exceedingly difficult to arrest it either by low temperature or by carbon dioxide storage.

The results herein reported establish for freshly harvested Bartlett pears a carbon dioxide tolerance that varies with storage temperature, concentration of carbon dioxide, length of exposure, and period of subsequent storage. Fruit destined for immediate consumption can be held at 45° F. in air for 15 to 20 days, in 10 percent gas for 20 to 30 days, and in 20- and 35-percent gas for 30 days or longer; and at 65° in air for 10 days and in 20-percent gas for 20 days. In each instance the fruit will ripen or may be ripened without impairment of flavor or dessert quality. Great differences, however, exist in the potential storage life of the fruit as a result of the various treatments. When it is desired to hold Bartlett pears for an additional period of storage at 32°, following intervals of exposure at harvest to various temperatures, periods of delay, or concentrations of gas, it becomes necessary to reevaluate their tolerance of these conditions. These investigations indicate that Bartlett pears can be held for the following periods in storage at 32°: 10 to 20 days after holding at 45° for 10 days; 38 to 40 days after holding at 45° in 10-percent of carbon dioxide for 10 days; 60 to 70 days after holding at 45° in 20-percent gas for 10 to 20 days; 60 to 70 days after holding at 45° in 35-percent gas up to 30 days; 10 to 20 days after holding at 65° in 20-percent gas for 10 days. It should be emphasized, however, that these gas tolerances represent maximum values and that they apply only to pears of best storage quality when harvested and handled under optimum conditions. In commercial practice, the industry would find it difficult to meet these standards; therefore, the period of gas storage and subsequent air storage at 32° would be proportionately less.

Bartlett pears have a tendency to develop severe surface scald when improperly handled (*10*). In the present investigations carbon dioxide always had a marked tendency to prevent the appearance of surface scald in the gas-stored fruit. This tendency persisted even during subsequent storage at 32° F. and during ripening at 65°. A recent report by Kidd, West, and Trout (*15*) substantiates these observations. Evidently carbon dioxide initiates some metabolic change in the fruit, following which normal ripening occurs without the appearance of surface scald. Acetaldehyde, as shown by Harley and Fisher (*10*), is usually associated with surface scald in Bartlett pears. There may be an interesting relation between carbon dioxide storage, depression of surface scald, and change in acetaldehyde content; such a suggestion, however, must also recognize the "CO_2-zymasis" work of Thomas (*24*), from the results of which he reports excessive accumulation of acetaldehyde in apples during storage in higher concentrations of this gas.

While Miller and Brooks (*21*) indicate that carbon dioxide treatment has no effect on the acidity of cherries, and Miller and Dowd (*22*) find no difference in the carbohydrate transformation of gas-stored peas, corn, and peaches, the results herein reported show that this gas does to a marked degree depress protopectin hydrolysis in pears. Such retardation from treatment in gas concentrations of 35 percent at 45° F. approximates that obtained by immediate storage at 32°.

Retardation of protopectin hydrolysis offers an explanation of the manner in which carbon dioxide may arrest softening and ripening of pears exposed to it. Although the suggestion was made by Hill (*11*) in 1913, this is the first instance, so far as the authors know, wherein carbon dioxide has been shown to retard markedly the formation of soluble pectin in stored fruit. A definite correlation also exists in pears between degree of ripeness and the amount of soluble pectin formed. From the data presented in tables 6 and 7, it is suggested that the amount of soluble pectin in Bartlett pears may be a significant index of the potential life of that fruit.

SUMMARY

This paper reports the results of storage, ripening, and soluble-pectin studies with Bartlett pears, in which temperature, concentration of carbon dioxide, and period of exposure have been varied.

When this variety was held at 45° F. for 20 days in 20 percent of carbon dioxide or for 30 days in 35 percent of carbon dioxide its potential storage life was not significantly different from that of fruit stored at 32° immediately after harvest. Freshly harvested fruit receiving such treatment may be subsequently stored at 32° and ripened at 65° without impairment of dessert quality.

The recommendation is made that whenever freshly harvested Bartlett pears are to be held at transit or storage temperatures materially higher than 30° to 32° F., and curtailment of ripening processes is desirable, carbon dioxide in a concentration of approximately 20 percent should be added to the storage air.

Carbon dioxide reduced surface scald in pear fruits.

There was a direct relation between the degree of ripeness and the amount of soluble pectin formed in Bartlett pears. Soluble pectin increased more than thirtyfold during ripening and then decreased with progressive senescence. Carbon dioxide retarded ripening by curtailing the processes associated with hydrolysis of protopectin. The soluble pectin content of fruit stored at 45° F. in 35 percent of carbon dioxide was comparable to that of fruit stored immediately at 32°.

The suggestion is made that a determination of soluble pectin in Bartlett pears may prove to be a valuable index of the degree of ripeness or of the potential storage life of the fruit at any given time.

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USE OF THE DILATOMETER IN MEASURING THE EXTENT OF FREEZING IN ICE CREAM AND RELATED PRODUCTS [1]

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INTRODUCTION

Although several workers have studied the extent to which ice creams are frozen at various temperatures, the results reported are incomplete, and the data are usually fragmentary. The present study, though likewise incomplete, is somewhat more extensive than previous reports in that samples of ice cream, ice milk,[3] and water ices (hereafter called simply "ices") have been included; in addition, observations have been made over a wider temperature range than in most of the other studies and the application of the dilatometer for measuring the extent of freezing seems to have certain advantages over the previous methods used. The results given in this report were obtained for the purpose of answering requests for more reliable information concerning the freezing of ice cream and related products.

HISTORICAL REVIEW

Various methods have been used in measuring or calculating the amount of ice formed at various temperatures in ice cream and related products. Hall (*9*),[4] observing temperature changes caused in a given amount of water by adding known amounts of ice cream at various temperatures, was able to approximate the amounts of ice formed in ice cream. Zoller (*15*) reported results obtained with the calorimeter, while Leighton (*11*), using the results reported by Pickering (*14*), devised a means of calculating the amount of ice formed on the basis of freezing-point determinations with mixes of known composition. Cole (*4*) separated the solid and liquid portions of ice-cream mixes at various temperatures either by centrifugation or by filtration under pressure, and arrived at values for the amount of ice formed over a limited temperature range.

Although the dilatometer has been widely utilized, in no report found by the author had it been used in measuring the amounts of ice formed in frozen dairy products. The fact, however, that Foote and Saxton (*6*, *7*, *8*) had determined with it the amount of water frozen in lampblack and inorganic hydrogels, and that Bouyoucos (*1*, *2*) had measured with it the amounts of soil moisture frozen at various temperatures, suggested its use in this study. This paper

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[2] The author is indebted to Bernice Fry, who made determinations on part of the experimental samples; to Dr. N. E. Edelfsen, irrigation division, University of California, who proposed helpful changes in the design of the dilatometer and in the manuscript during its preparation; to Dr. G. A. Richardson, dairy-industry division, and Dr. C. S. Bisson, chemistry division, University of California, for reading and constructively criticizing the manuscript; and to Dr. Max Kleiber, animal industry division, University of California, who did most of the glass blowing during the construction of the dilatometer, and whose criticisms of the theoretical considerations in the manuscript were very helpful.

[3] Ice milk is a frozen dairy product similar to ice cream except that its fat content is much lower. In California the minimum fat in ice milk is 4 percent; in ice cream, 10 percent.

[4] Reference is made by number (italic) to Literature Cited, p. 153.

reports some results obtained by measuring with a dilatometer the volume changes that accompany the freezing of ice cream and related products.

EXPERIMENTAL METHODS

The mixes used were prepared in accordance with commercial practices. Fresh milk, cream, and condensed skim milk were used as the sources of milk products; sucrose and gelatin as the other ingredients for ice cream and ice milk. No dairy products were used in the ices; but corn sugar was added along with the sucrose, and agar along with the gelatin. The ice mixes were heated sufficiently to dissolve the gelatin and agar used as stabilizers; the other samples were pasteurized at approximately 65° C. for 30 minutes, homogenized at pasteurization temperature, and cooled to about 5°. The ice-milk mixes were homogenized at 2,500 pounds pressure per square inch, a single-stage valve being employed. The double-stage homogenizer used for the ice-cream mixes was operated at 2,000 pounds pressure per square inch on the first stage and 750 pounds per square inch on the second stage for the mixes containing about 12 percent of fat; 1,800 pounds pressure per square inch on the first stage and 500 pounds per square inch on the second stage for the mixes containing about 18 percent of fat. The mixes were processed 1 or 2 days before being used in the dilatometer and were held at about 2° during this interim.

Since air in the sample would influence the volume changes accompanying freezing, the following precaution was taken before the sample was admitted to the dilatometer: It was placed under 25 to 28 inches of vacuum and heated sufficiently to start ebullition, then immediately cooled, the vacuum being maintained, and transferred to a weighing burette. This procedure did not completely eliminate, though it did reduce, the air in the samples. Since it was followed uniformly, however, the expansion factor used for the apparatus would partly correct for the errors introduced by this method.

The dilatometer used in these determinations is illustrated in figure 1. In making a determination compartment *a* was filled, to the mark indicated, with a portion of the sample. By opening the stopcock between compartments *a* and *b* and adjusting the leveling bulb, *d*, the desired amount of sample was admitted into compartment *b*. Then, after closing this stopcock, the weight of the sample in *b* was determined by refilling compartment *a* to the original mark from a weighing burette. Compartment *a* was then emptied by properly adjusting stopcock *e*. By means of the leveling bulb *d* and the three-way stopcock *f* the desired amount of mercury was admitted into capillary *c*, and stopcock *f* was then adjusted so that any change in volume in compartment *b* was measured by change in position of the mercury in the capillary.

The temperature of the sample was maintained at the desired levels by immersing the dilatometer in a brine bath so that the top of the sample in compartment *b* was 4 cm below the surface. The bath in turn was cooled by a refrigerated ice-cream cabinet in which it was placed. In certain instances solid carbon dioxide was added directly to the bath to hasten the cooling process. The temperature of the cabinet was maintained below that desired in the bath, but a thermo-

regulator was used to operate a heating element by means of which the bath temperature could be maintained at any desired point over the range 0° to −30° C. to within ±0.01°, or closer, as a result of supplementing the control by manual manipulation. Uniform temperature throughout the bath was assured by a motor-driven stirrer. For the temperature measurements over the range from −30° to approximately −10° a mercury thermometer graduated in 0.1° was used. It was found to be accurate to within one division on the scale. Over the range from approximately −10° to 0° or slightly higher,

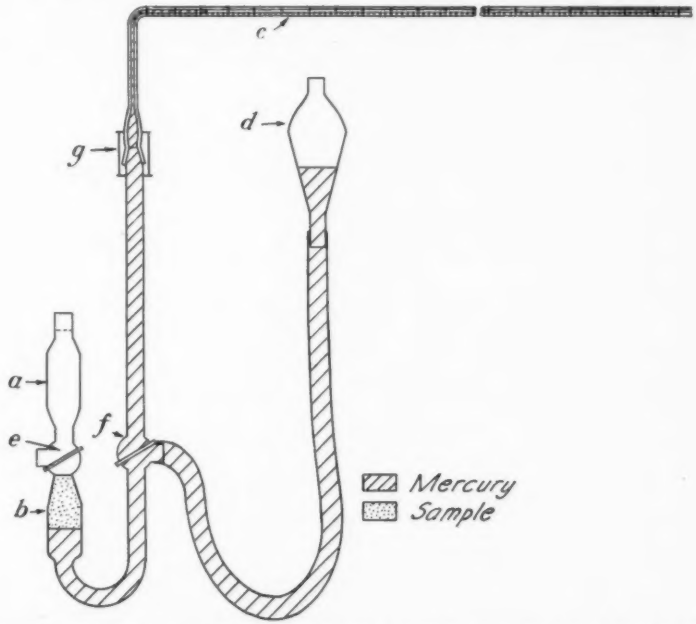

FIGURE 1.—The dilatometer: *a*, Compartment in which sample is measured; *b*, compartment in which sample is frozen; *c*, capillary tube in which the expansion is measured; *d*, leveling bulb; *e* and *f*, three-way stopcocks; *g*, ground-glass joint.

Heidenhain and Beckmann thermometers graduated in 0.01° were used.

Besides the sample of mix used in the dilatometer, other portions of the same mix were concentrated by evaporation under vacuum; and freezing-point and total-solids determinations were made on these as a basis of checking the results obtained in the dilatometer. With the ice mixes these concentrated portions were prepared by omitting part of the water required for the complete mixes. Although this second procedure was occasionally followed with ice-cream and ice-milk mixes, concentrated portions were also prepared by evaporating the samples according to the first method.

The freezing-point determinations in practically all cases were made with a Hortvet cryoscope. In a few instances, however, where the freezing points of the samples were low as a result of the mixes being

highly concentrated, a small portion of the sample was cooled in a brine bath until freezing began. Temperature readings taken at regular intervals were used in finding the freezing points of such samples. Duplicate or triplicate determinations were made in all cases.

In obtaining the dilatometer data, readings were taken at intervals of one-half hour or longer, and a sufficient number were taken at each temperature to make certain that no further changes in volume occurred. A constant reading was considered to indicate a state of equilibrium. Cooling curves did not deviate significantly from melting curves for the same samples.

Each sample which had been frozen and melted was supercooled and refrozen to determine whether or not the expansion the second

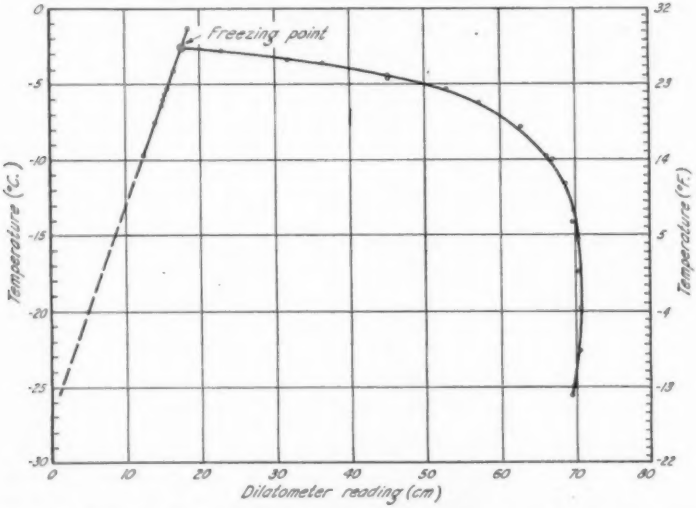

FIGURE 2.—Relation of dilatometer readings with supercooled sample to such readings after freezing. Sample M–7; 12.15 percent of fat, 38.14 percent of T. S.; freezing point, −2.55° C.; weight in dilatometer, 3.8504 g.

time would differ from the first. In a few cases samples were refrozen several times. For each sample reported, 30 to 50 points were carefully determined thus in the dilatometer as a basis for constructing the curve from which to calculate the amount of ice formed in the sample over the temperature range studied. Usually from 7 to 10 days were required for completing the measurements for each sample.

The basis for calculating the amount of ice formed in the sample under observation from the dilatometer readings is illustrated in figure 2, which represents graphically the dilatometer data obtained with sample M–7. The straight dashed line drawn through the points to the left represents data taken before the sample had been frozen and after it had been melted. Since most of these observations were made below the freezing point of the sample, the line is called the supercooled line. The points on the curve to the right represent readings obtained during both the freezing and the melting of the sample.

The horizontal distance at a given temperature from the supercooled line to the curve represents the linear expansion of the mercury capillary. This, multiplied by the factor representing the cross-sectional area of the capillary, gives the volumetric change that accompanies freezing at that temperature. Then, considering the size of the sample and the expansion factor representing the change in volume that accompanies the freezing of 1 g of water, the amount of ice formed at a given temperature is calculated. When a sufficient number of such values have been taken, another graph can be constructed as in figure 4 to represent the relation of temperature to the amount of ice formed. As will be shown presently, it was not difficult to get duplicate runs of the same mix to check in the dilatometer; but slight variations in the composition of mixes prepared at different times made these "duplicates" more difficult to check. All analyses for fat and total solids were made by the Mojonnier method and were run in duplicate.

EXPERIMENTAL RESULTS

STANDARDIZING THE APPARATUS

To standardize the dilatometer for subsequent use with experimental samples, the expansion factor accompanying the change of water into ice was determined. Water was boiled and cooled just before it was used for this purpose. The following expansion factors calculated as cubic centimeters per gram of water frozen were obtained: 0.0945, 0.0949, 0.0944, 0.0943, 0.0946.[5]

The close agreement of these values indicates the extent to which it was possible to duplicate results by this method.

As a further check on the dilatometer, a sucrose[6] solution (approximately 20 percent) was frozen in the apparatus. When the expansion factor of 0.0945, obtained with water, was used to calculate the amount of water frozen from this solution, the results differed from those calculated from International Critical Tables (*13, v. 4, p. 263*) data by about 1.3 percent. It was decided, therefore, to standardize the expansion factor for the dilatometer so that the results obtained with the sucrose solution would agree better with those computed from these data. An expansion factor of 0.0933 cubic centimeters per gram of water frozen gave close agreement (fig. 3). These results are tabulated as a convenience in calculating the amount of ice formed by taking into account freezing-point data on sucrose solutions (table 1).

TABLE 1.—*Relation of temperature to the amount of water frozen from a 20-percent sucrose solution and to the concentration of sucrose in the fraction remaining*

Temperature (° C.)	Water frozen	Ice in sample	Sucrose concentration in unfrozen fraction of sample		Temperature (° C.)	Water frozen	Ice in sample	Sucrose concentration in unfrozen fraction of sample	
	Percent	*Percent*	*Percent*	*Mols per 1,000 g water*		*Percent*	*Percent*	*Percent*	*Mols per 1,000 g water*
−1.49 [1]	0	0	20.0	0.736	−12.5	83.7	67.0	60.6	4.49
−2.0	23.0	18.4	24.5	.948	−15.0	86.2	69.0	64.5	5.30
−3.0	47.2	37.8	32.2	1.39	−17.5	87.4	69.9	66.4	5.77
−4.0	58.5	46.8	37.6	1.76	−20.0	88.9	71.1	69.2	6.56
−5.0	65.8	52.6	42.2	2.13	−22.5	89.5	71.6	70.5	6.97
−6.0	70.7	56.6	46.1	2.50	−25.0	90.2	72.1	71.7	7.40
−10.0	80.5	64.4	56.2	3.75	−26.8	90.6	72.5	72.7	7.77

[1] The freezing point of the solution was − 1.49° C.

[5] Three of these values were obtained by the author, and two by Bernice Fry, who assisted with part of this study.

[6] Baker's analyzed C. P. sucrose was used in preparing this solution.

Since the ice cream and related products included in this study resemble this solution more than they do water, and since the same temperature range was covered in both cases, the value of the expansion factor obtained with the sucrose solution was used as a basis for calculating the values given in this paper.

In presenting the data obtained with the experimental samples, the gross analyses for fat and total solids are given for each sample in

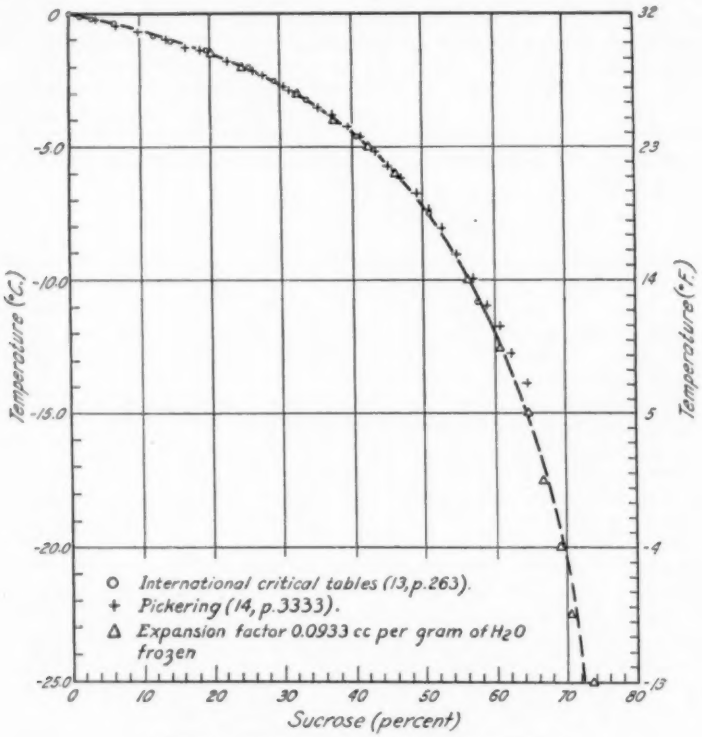

FIGURE 3.—Freezing-point lowering of sucrose solutions.

addition to its freezing point. The observations with the dilatometer and the freezing points on various concentrated portions of the same sample are in most instances presented graphically. These comparisons indicated a fairly satisfactory agreement between the two methods used. Especially is this true in the temperature range just below the original freezing points of the mixes. In some cases the agreement is good at temperatures as low as −15° C., but ordinarily the deviation here is greater than at the higher temperatures.

ICE-CREAM MIXES

Ice-cream mixes containing approximately 12 percent of fat and 38 percent of total solids are commonly used in making commercial ice

cream. In this study, measurements were made on five mixes of this type. Each was prepared separately, and although they were approximately the same in composition, each differed slightly from the others.

The data presented in table 2 were obtained with sample M–8 from duplicate runs in the dilatometer. These data are fairly representative of the group, and their close agreement indicates the precision of the method. The freezing-point determinations (not given in this table) also checked closely with the dilatometer data.

TABLE 2.—*Relation of temperature to the amount of water frozen in sample M–8* [1]

Temperature (° C.)	Water frozen		Ice in sample		Temperature (° C.)	Water frozen		Ice in sample	
	Trial 1	Trial 2	Trial 1	Trial 2		Trial 1	Trial 2	Trial 1	Trial 2
	Percent	*Percent*	*Percent*	*Percent*		*Percent*	*Percent*	*Percent*	*Percent*
−2.47	0	0	0	0	−10.0	72.0	71.9	44.7	44.6
−3.0	18.4	18.1	11.4	11.2	−12.5	77.6	77.1	48.2	47.8
−3.5	28.3	28.2	17.5	17.5	−15.0	81.2	80.9	50.3	50.2
−4.0	36.0	35.8	22.3	22.2	−17.5	84.1	84.0	52.2	52.1
−5.0	48.0	47.6	29.8	29.5	−20.0	86.5	86.3	53.6	53.5
−6.0	55.6	55.2	34.5	34.3	−25.0	90.2	89.6	56.0	55.6
−7.5	63.5	63.3	39.4	39.2					

[1] The mix was found by analysis to contain 12.33 percent of fat and 37.98 percent of total solids. Its freezing point was −2.47° C. For the first and second determinations 4.902 and 4.648 g, respectively, were used.

The data from two other samples in this group are presented to show the agreement obtainable between observations on separate mixes which are very similar in composition. Table 3 gives the data secured with samples M–2 and M–7, the freezing points of which were −2.58° and −2.55° C., respectively. As can be seen also by comparing tables 2 and 3, some differences were found in the amount of ice formed in sample M–8 and in the two samples just mentioned. The differences apparent at the higher temperatures, however, become less significant in the lower temperature ranges.

Observations on other samples also indicated that samples having the same percentages of fat and total solids may have different freezing points, because of differences in the amount of soluble and ionizable constituents. In these cases the higher the freezing point of the mix the greater the amount of ice formed at a given temperature.

TABLE 3.—*Relation of temperature to the amount of water frozen in ice cream samples M–2 and M–7 containing approximately 12 percent of fat and 38 percent of total solids*

Temperature (° C.)	Water frozen in sample—		Ice in sample—		Temperature (° C.)	Water frozen in sample—		Ice in sample—	
	M–2 [1]	M–7	M–2	M–7		M–2 [1]	M–7	M–2	M–7
	Percent	*Percent*	*Percent*	*Percent*		*Percent*	*Percent*	*Percent*	*Percent*
−3.0	13.1	13.1	8.1	8.1	−12.5	75.3	75.4	47.3	46.7
−3.5	24.5	24.1	15.2	14.3	−15.0	80.0	79.0	49.5	48.9
−4.0	33.2	31.4	20.6	19.4	−20.0	85.0	84.3	52.7	52.2
−5.0	45.2	45.2	28.0	28.0	−25.0	88.5	87.8	54.8	54.3
−7.5	61.4	61.0	38.0	37.7	−25.5	.....	88.1	.....	54.5
−10.0	70.8	69.8	43.8	43.2	−26.7	89.4	.....	55.4	.....

[1] Sample M-2 contained 12.0 percent of fat and 38.05 percent of total solids, and its freezing point was −2.58° C.; composition of M–7 given in legend of fig. 4.

The freezing-point data and the dilatometer measurements on sample M–7 (fig. 4) indicate the agreement possible between the two types of measurements on the same sample. Freezing-point determinations were not made on this sample below −7° C.

Under commercial conditions ice cream containing about 18 percent of fat and from 40 to 42 percent of total solids is manufactured and often sold as "catering" or "caterer's" ice cream. Observations were made on four mixes similar to this in composition. They varied

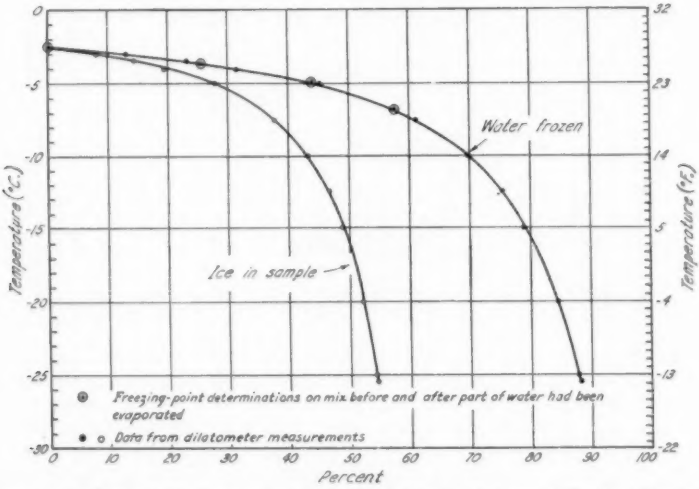

FIGURE 4.—Relation of temperature to percentage of water frozen and to percentage of ice in ice cream containing 12.15 percent of fat and 38.14 percent of total solids; freezing point, −2.55° C.; sample M–7.

enough so that the results from one sample could not be used as a check on the others. Figure 5 gives the results obtained with sample M–12. Freezing data agree closely with those secured with the dilatometer. The original freezing point of this mix, however, was higher than that of some others in this group. One should consider this fact before applying such data to other samples.

ICE-MILK MIXES

Ice milk, being comparable to low-fat ice creams, would be expected to give results resembling those obtained with such products. The results with two samples of ice milk having approximately the same composition are given here to confirm the statement. Table 4 shows the data for samples M–3 and M–6 to agree closely. Figure 6 gives the relation between the freezing-point data and those obtained with the dilatometer for sample M–3. Incidentally, the data approximate rather closely those given for ice-cream mix M–8 (table 2). Although these ice-cream and ice-milk samples differ widely in composition on the basis of analyses, their freezing points are −2.47° and −2.50° C., respectively. This fact probably explains the similarity in the results obtained.

TABLE 4.—*Relation of temperature to the amount of water frozen in ice milk in samples M–3 and M–6*

Temperature ° C.	Water frozen in sample—		Ice in sample—		Temperature ° C.	Water frozen in sample—		Ice in sample—	
	M–3	M–6 [1]	M–3	M–6 [1]		M–3	M–6 [1]	M–3	M–6 [1]
	Percent	*Percent*	*Percent*	*Percent*		*Percent*	*Percent*	*Percent*	*Percent*
−3.0	17.4	17.9	11.7	12.0	−10.0	71.9	72.4	48.5	48.5
−3.5	27.6	28.3	18.6	19.0	−15.0	81.0	81.2	54.6	54.4
−4.0	35.8	36.2	24.2	24.3	−17.5	83.7	84.3	56.1	56.5
−5.0	47.6	47.9	32.1	32.1	−20.0	86.0	86.4	58.0	57.9
−6.0	55.3	55.6	37.1	37.3	−25.0	89.2	88.9	60.2	59.6
−7.5	63.0	63.5	42.5	42.6	−28.0	90.3	.....	60.9	.....

[1] M–6 contained 4.61 percent of fat and 32.99 percent of total solids. Its freezing point was −2.56° C. See legend of fig. 6 for composition of M–3.

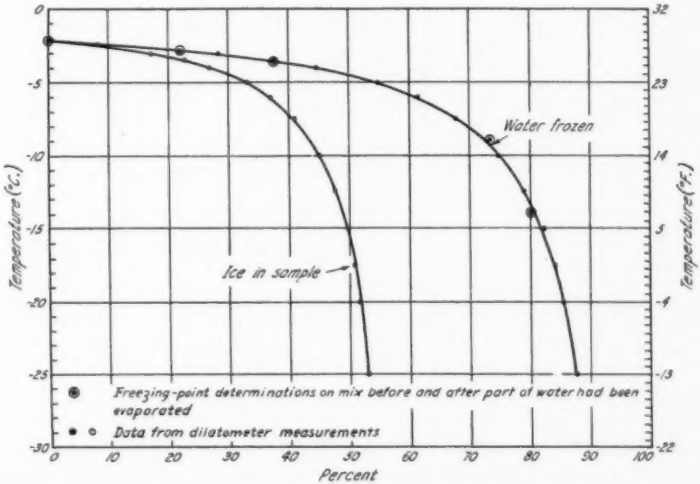

FIGURE 5.—Relation of temperature to percentage of water frozen and to percentage of ice in ice cream containing 18.68 percent of fat and 39.68 percent of total solids; freezing point, −2.13° C.; sample M–12.

ICE MIXES

Most manufacturers of ice cream make, in addition, ices or sherbets, or both. Sherbet mixes, however, are often made by simply adding ice-cream mix or other milk products to the mixes used in making ices. It seemed best, therefore, to obtain data for ices, since the results for sherbets would most likely be intermediate between those for ices and ice cream. The results obtained may not have general application, since considerable variation occurs in the composition of ices as made commercially. Some contain sucrose alone as the sweetening agent; others, combinations of sugars, such as sucrose and glucose. The composition may vary in other respects also, as, for example, in the addition of fruits, which are ordinarily used for flavoring.

Observations were made on four ice mixes prepared to contain approximately 23 percent of sucrose, 7 percent of glucose (corn sugar),

0.2 percent of gelatin, 0.2 percent of agar, and 0.5 percent of titratable acidity, calculated as citric acid. The results for one of these samples are given in figure 7. They differ markedly from those obtained with ice cream and ice milk, in that less water is frozen at a given temperature for the ices. The comparatively low freezing points of the ice mixes account for this difference.

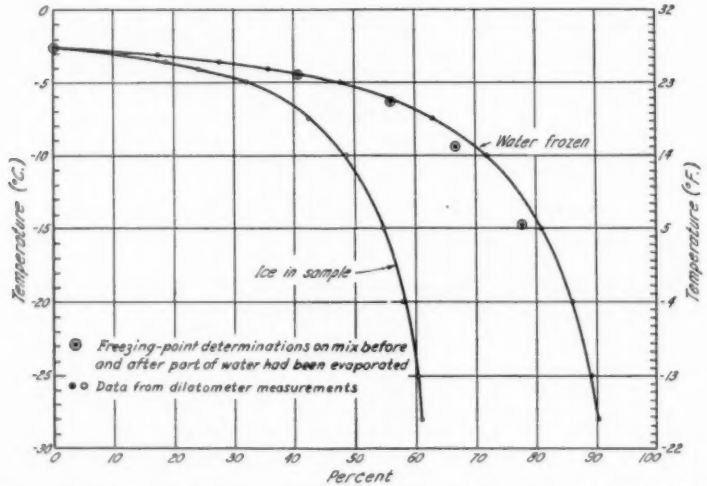

FIGURE 6.—Relation of temperature to percentage of water frozen and to percentage of ice in ice milk containing 4.55 percent fat and 32.55 percent total solids; freezing point, −2.50° C.; sample M–3.

THEORETICAL CONSIDERATIONS CONCERNING CHANGES IN VOLUME ACCOMPANYING FREEZING

The freezing process causes marked changes in concentration with respect to the substances in solution in the unfrozen portion of the sample. A given amount of solute is known to change the volume of a solution to which it is added to an extent which in some instances depends upon the concentration of the solution. Conceivably such changes might explain part of the changes in volume measured by the dilatometer during freezing.

These changes can be evaluated by a consideration of partial molal volumes or partial specific volumes, or they may be calculated directly from adequate specific volume data.

As a basis for understanding what changes occur during freezing let us start with 100 g of a 20-percent sucrose solution. Assume now that we remove successively from this solution either 5-g or 10-g quantities of water until the remaining solution consists of 20 g of sucrose and 5 g of water. (See columns 1 to 3, inclusive, of table 5.) If we assume further that these changes occur at constant temperature, then we can calculate the changes in volume which have occurred by taking into account the specific volumes and weights of the solution remaining at the various stages in the process.

Data for the specific volumes of sucrose solutions are not available over the temperature range desired, but they can be calculated for 20° C. from density data as reported in the International Critical

Tables *(13, v. 2, pp. 343–344)*. These values are given in column 4 of table 5. Utilizing such data, calculations were made to indicate the influence of concentration upon the change in volume of the solution. The results of these calculations are tabulated in columns 5 and 6.

In addition, either equation (1) or (2) given below can be used as a basis for calculating the values in columns 5 and 6. Using equation (1) it is necessary to evaluate the partial specific volumes or partial molal volumes of both components of the system, whereas with equation (2) only the partial molal volume of water need be evaluated. This was

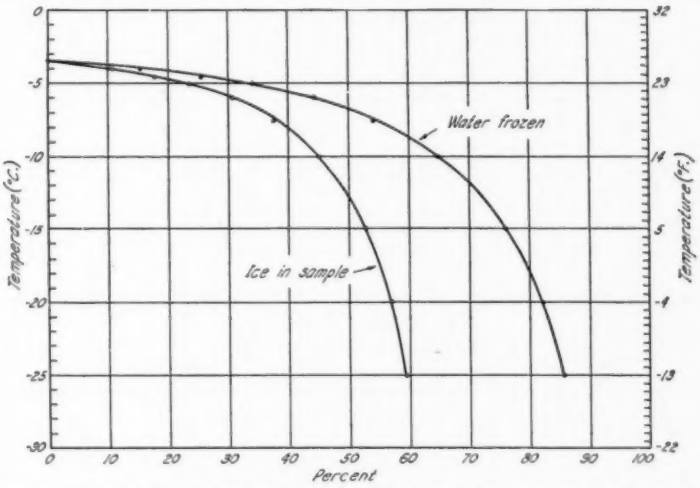

FIGURE 7.—Relation of temperature to percentage of water frozen and to percentage of ice in water ice. Sample M-16: No fat; 30.615 percent of total solids; freezing point, −3.48° C.

done by the method of intercepts as reported by Lewis and Randall *(12, pp. 38–40)*, using the specific volume data previously mentioned.

At any stage in the process the volume can be calculated by equation (1), assuming the temperature to be constant.

$$V=n_1\overline{V}_1+n_2\overline{V}_2 \tag{1}$$

Where

V = volume of the solution

$\overline{V}_1=\dfrac{\delta V}{\delta n_1}$ = partial molal volume of X_1

$\overline{V}_2=\dfrac{\delta V}{\delta n_2}$ = partial molal volume of X_2

n_1 = number of mols of X_1 (water in this case)

n_2 = number of mols of X_2 (sucrose in this case).

Obviously $\overline{V}_1$ and $\overline{V}_2$ can represent partial specific volumes if n_1 and n_2 indicate grams of the respective components. The values obtained by this equation agree very closely with those reported in column 5, the agreement depending upon the accuracy with which the partial molal volumes used in these calculations can be evaluated graphically.

TABLE 5.—*Theoretically calculated changes in volume accompanying freezing of sucrose solution* [1]

Weight of solution containing 20 g of sucrose	Weight of ice separated from 100 g of original solution	Concentration of sucrose in solution	Specific volume of solution	Volume of sucrose solution	Change in volume of solution accompanying removal of water	Volume of ice separated from solution (specific volume = 1.0962)	Volume of 100 g of mixture (solution + ice)	Increase in volume due to formation of ice	Decrease in volume of ice due to lowering of temperature	Decrease in volume of solution due to lowering of temperature	Net expansion due to formation of ice	Net expansion per gram of ice formed
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
Grams	*Grams*	*Percent*	*Cubic centimeters*	*Cubic centimeters*	*Cubic centimeters*	*Cubic centimeters*	*Cubic centimeters*	*Cubic centimeters*	*Cubic centimeters*	*Cubic centimeters*	*Cubic centimeters*	*Cubic centimeters*
100	0	20.000	0.92510	92.510	0	0	92.510	0	0	0	0	0
90	10	22.222	.91667	82.500	10.010	10.962	93.462	.952	.0012	.0107	.940	.0940
80	20	25.000	.90616	72.493	20.017	21.924	94.417	1.907	.0036	.0113	1.882	.0941
70	30	28.571	.89270	62.489	30.021	32.886	95.375	2.865	.0086	.0187	2.838	.0944
60	40	33.333	.87483	52.490	40.020	43.848	96.338	3.828	.0166	.0227	3.789	.0948
50	50	40.000	.85002	42.501	50.009	54.810	97.311	4.801	.039	.038	4.724	.0945
40	60	50.000	.81329	32.532	59.978	65.772	98.304	5.794	.074	.058	5.662	.0944
30	70	66.667	.75385	22.616	69.894	76.734	99.350	6.840	.166	.138	6.537	.0934
25	75	80.000	.70836	17.709	74.801	82.215	99.924	7.414	.24	.20	6.97	.093

[1] The calculated values in columns 1 to 9, inclusive, are based on the assumption that temperature remains constant. The values in columns 10 and 11 take into account changes in volume due to changes in temperature necessary to cause the desired freezing, assuming the initial temperature to be the freezing point of the original solution. The last 2 columns give the net changes in volume.

The following equation might also be used for these calculations:

$$dV=\overline{V}_1 dn_1+\overline{V}_2 dn_2 \qquad (2)$$

where

dV=change in volume of the solution

dn_1 and dn_2 refer to the changes in the number of mols of water and sucrose, respectively

$\overline{V}_1$ and $\overline{V}_2$ have the same significance as in equation (1).

It will be recalled that as freezing progresses the amount of sucrose in solution remains constant even though its concentration in the solution increases. On this basis $dn_2=0$. Hence the equation for the particular case becomes

$$dV=\overline{V}_1 dn_1$$

or

$$\Delta V=\int_a^b \overline{V}_1 dn_1 \qquad (3)$$

Evaluating equation (3) graphically gives values almost identical with those of column 6.

Both equations (1) and (2) can be extended to represent more complex systems such, for example, as a solution containing lactose and possibly other dissolved substances in addition to sucrose. Equation (2) is of special interest in this case. In its general form it may be written

$$dV=\overline{V}_1 dn_1+\overline{V}_2 dn_2+\overline{V}_3 dn_3+\overline{V}_4 dn_4 \ldots \qquad (4)$$

If water is the only component of the system which is removed from solution then dn_2, dn_3, dn_4, etc., all become zero and the equation is again reduced to

$$\Delta V=\int_a^b \overline{V}_1 dn_1$$

In other words, we can neglect the partial molal volumes of components other than water if we know that water is the only component separating from solution during the freezing process.

If we consider that the water which is removed is converted into ice without changing the temperature of the system, then the volume of the mixture of ice and solution will be the sum of the volumes of the solution and ice at the original temperature. Ice was considered to have a specific volume of 1.0962 at 20° C. (This value was obtained by using 0.00027 as the thermal coefficient of cubic expansion for ice and extrapolating from 0° to 20°.) The results of these calculations are given in column 8 of table 5 and were obtained by adding the values in columns 5 and 7.

By subtracting from the respective values in column 8 those given in column 5, data are obtained which may be considered to represent the theoretical increases in volume accompanying the formation of ice at constant temperature. Actually, however, the freezing process is

accompanied by lowering of temperature, which in turn causes decreases in volume of both ice and unfrozen solution.

By taking data from figure 3 as a basis for deciding the changes in temperature necessary to remove from solution the required amount of water as ice, and noting the changes in thermal coefficient of expansion of ice covering this range in temperature (*13, v. 3, p. 43*), values have been calculated to show the decrease in volume of ice as compared with its volume at the original temperature. These data are given in column 10. Adequate data are not available for a consideration of the influence of temperature upon the volume of the solution, but by using data for a slightly higher temperature (0° to 20° C.) as reported by Karas (*10*) it has been possible to approximate these changes in volume. The results of these calculations are given in column 11.

Taking into account the values in columns 10 and 11 as a basis for modifying those in column 9, the net increase in volume due to the formation of ice is found, as shown in column 12. The expansion per gram of ice formed is tabulated in column 13. These values deviate only slightly from 0.0944 cc, which is the increase in volume per gram of ice formed at the initial temperature in this study.

The foregoing calculations indicate that the volume changes accompanying freezing are due primarily to the change in state of the water in solution, that is, its separation in the form of ice. The values calculated theoretically also seem to justify the use of a single expansion factor per gram of ice formed over the temperature range considered. Further justification for this assumption is to be found in the agreement between freezing-point data and dilatometer data obtained by using a single expansion factor over the temperature range employed in this study.

DISCUSSION

Attempts to measure the amount of ice formed in ice cream and related products are beset with difficulties, and the use of the dilatometer does not remove them. It does have certain advantages, however, over earlier methods. In standardizing the apparatus, accurate freezing-point data for sucrose solutions were not available for temperatures much below −13° C., yet an attempt was made to measure the amount of ice formed in this work down to −25°. Obviously this check could not be applied to results at the lower temperatures. The data obtained, however, agree with the values that would be expected by extrapolating beyond the values given in the International Critical Tables (*13, v. 4, p. 263*), as shown in figure 3.

If the densities of water and ice are considered at 0° C., the theoretical expansion factor accompanying the change of 1 g of water into ice would be 0.0907 cc. It is difficult to say why the expansion factor obtained with the dilatometer differed from the theoretical expansion factor for water to ice. Air in the system was possibly a contributory factor, since the solubility of air in ice is low as compared to its solubility in the solution at the same temperature. As more of the water from the solution was frozen, it would increase the amount of air set free, thereby giving an expansion factor greater than would otherwise be expected. By setting up a more elaborate means of exhausting the samples of air one could determine whether or not air was a contributing factor. In this connection, however, it may be mentioned that Foote and Saxton (*6*), working with inorganic hydrosols

under somewhat similar conditions, obtained an expansion factor of 0.09325 cc per gram of water changed to ice, as compared with 0.0933 cc used in this study, whereas Bouyoucos (*2*), working with soils, used an expansion factor of 0.10 cc per gram of water frozen.

As already indicated, Leighton (*11*) has suggested a method of approximating the amount of ice formed in ice cream. His calculations are based, among other things, upon the freezing-point depression data for sucrose solutions given by Pickering (*14*). The lowest temperature reported by this author, however, is −13.8° C. Conceivably such calculations might be extended to lower temperatures—for example, −25.0° to −15.0°—as a result of utilizing the data reported in table 1.

It was difficult to initiate freezing while making freezing-point determinations on some of the samples concentrated by the evaporation method. This trouble was presumably caused in part by the high concentration of gelatin and the accompanying increase in viscosity of the samples. For this reason the freezing-point determinations on highly concentrated samples cannot be considered as reliable as those made on the samples before they were concentrated.

In evaluating the partial molal volumes for sucrose and water at various concentrations of sucrose the data used were taken at 20° C. No data from which these values can be calculated are available for the temperature range in these experiments. Such data, if available, might perhaps make a significant difference in the calculated values reported in the section dealing with theoretical considerations. The partial molal volumes of the components other than sucrose and water were not considered.

Zoller (*16*) in 1921 advanced the idea that the percentages of water frozen in a sample of ice cream at a particular temperature would not be equal in all cases. He states (*16, p. 45*):

> The temperature at which the mix is drawn from the machine may be the same (for the same ice cream mixture) in the case of a dozen freezings and yet some may be soft with 15 per cent. of the water frozen while some may be stiff with 40 to 50 per cent. of the water frozen into ice.

Bradley and Dahle (*3*) have recently subscribed to this belief as a basis for explaining differences in texture of ice cream frozen in a continuous (Vogt) freezer as compared with freezing in a batch freezer.

Although such differences would be expected if one or more of the substances dissolved were to crystallize out of solution, it seems unlikely, under commercial conditions, that any significant differences would occur at a given temperature while the mix in question is in the freezer. In the first place, vigorous agitation takes place while the sample is being frozen whether a batch or a continuous-type freezer is employed. In the second place, ice crystals would usually be present in the freezer to initiate freezing as soon as the temperature of the mix had been lowered sufficiently. Although ice would not be present at the beginning of a day's run, it would be present at the beginning of each subsequent run with the batch freezer and continuously after freezing had started in the continuous freezer. As both these factors would tend to prevent supercooling, it might be expected that if different portions of the same mix were frozen in batch and in continuous freezers and withdrawn from these freezers at the same temperature, the percentage of water frozen would be the same in both cases. Conclusive proof of this statement is not available from

the data presented, since the conditions under which freezing occurred in the dilatometer were not comparable in many respects to those under which mixes are frozen commercially. Considerable variation did occur, however, in the rate of freezing of the same sample in this apparatus at different times. In such cases, when equilibrium had been established for a certain temperature, the same amount of ice formed no matter whether the freezing was accomplished rapidly or slowly.

If lactose or any other component present, other than water, were to crystallize out of solution in one trial and not in another, even though portions of the same mix were frozen, then the same percentages of ice would not be formed in the two portions of this sample even if examined at the same temperature. In this study, however, there was no indication that any other component besides water crystallized while the measurements were being made in the dilatometer, although the concentrations of sucrose and lactose were greater in the experimental samples than would be permitted by saturated solutions at these low temperatures. A given sample refrozen several times formed practically the same percentages of ice in successive determinations whether the freezing or the melting curves were considered.

The trend in commercial practice has definitely been toward fast-frozen ice creams. Most of the new freezers are designed to permit rapid heat transfer. Some are so constructed that the ice cream can be regularly withdrawn from the freezer at −6.0° to −5.5° C. (21.2° to 22.1° F.), which for a sample like M–8 would mean that 55 to 48 percent of the water had been frozen. The common practice, where batch freezers have been used, has been to draw ice cream at from −4.0° to −3.3° C. (24.8° to 26.1° F.), which would show from 36 to 24 percent of the water frozen for the sample M–8. The advantage of rapidly freezing as much of the water as possible has been indicated previously (*3*, *4*, *5*), although many manufacturers still overlook the benefits obtainable by this practice.

Certainly the installation of air-circulating systems in hardening rooms as well as blast tunnels, and the use of relatively low temperatures, are desirable practices as regards the improvement of ice-cream texture. Even here, however, the rate of freezing is slow as compared with the rate at which ice is formed in the freezer.

The data in this paper should emphasize the differences in the amounts of ice formed at various temperatures. These differences, if correlated with the rate at which freezing occurs in practice, may help to determine the effects of such variations upon the quality of the finished products.

SUMMARY

The use of the dilatometer method as a basis for measuring the amount of ice formed in ice cream and related products has been described.

By this method, measurements were made on nine ice-cream, three ice-milk, and four water-ice samples. The results presented show the percentages of water frozen in various mixes over a temperature range from about −25° to 0° C.

On the basis of the observations with sucrose solutions, data are presented to show the relation between freezing-point lowering and

concentration at temperatures below that given by Pickering (*14*) or reported in the International Critical Tables (*13*). A suggestion is made as to how these additional data can be used in calculating the amount of ice formed in ice cream.

The results given may serve as a basis for improving commercial practices in freezing such products as ice cream, since quality is influenced by the amount of ice frozen at certain stages of manufacture and distribution.

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A METHOD FOR EXTRACTING GROWTH SUBSTANCES FROM PIGMENTED TISSUES [1]

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That natural growth substances in green plants occur in different concentrations has not yet been actually proved, but there are many indications that such is the case. Two methods to demonstrate the presence and concentration of growth regulators are in use: (1) The diffusion method (Stark (*10*),[3] Seubert (*8*), and Went (*12*)), and (2) the extraction method (Nielsen (*7*), Kögl, Erxleben, and Haagen-Smit (*5*), and Thimann (*11*)) and others.

The diffusion method has been used lately by many investigators (e. g., Avery, Burkholder, and Creighton (*2*) to demonstrate the regulatory effect of stem growth; Delisle, 1937, (*3*) in his investigation on leaf development, etc.). In some cases the results differ from those obtained by the extraction method on "colorless" plants. The differences may be accounted for by the fact that the diffusion method gives information only on the transport of the substances, and not on the actual concentration. If the transport is low, the concentration may be very high, and vice versa (cf. Söding (*9, p. 841*)).

The above-mentioned extraction methods have been used for the lower plants and for etiolated higher plants. When green plants have been extracted very low concentrations have been found, or the curvatures were irregular, or, as many investigators have noted, the curvatures were positive. Avery's extractions of *Nicotiana* leaves (*1*) gave only relative values, as can be seen by a comparison of his values with those obtained by diffusion. Jahnel (*4*) obtained very variable results from extractions of potato, except in one case.

The extraction method described below permits a more precise determination of the actual amount of growth substances in pigmented plants than is possible by the methods discussed above. A trial of the other methods indicated that the main trouble begins when chlorophyll, or, in the case of potatoes, some strongly adsorbing or oxidizing substance is extracted with the auxin. To obviate this difficulty the tissue is frozen with solid carbon dioxide. The carbon dioxide atmosphere prevents the activity of oxidizing agents, and the freezing makes the tissue very brittle and permits a thorough grinding. After the grinding, an excess of slightly acidified water is added which thaws the tissue slowly and in the meantime dissolves the auxins, apparently before other substances of the extract can destroy them. Before the temperature has risen the mixture is filtered through a Büchner filter and washed out at least twice with water at a temperature of about 0° C. The filtrate is then washed three times with ether or chloroform. These solvents are each time separated from

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[2] The writer wishes to express his thanks to Dr. N. L. Drake for helpful suggestions in the course of the work.
[3] Reference is made by number (italic) to Literature Cited, p. 157.

the water layer and contain most of the growth substance. The solvent is then evaporated until about 0.1 cc is left. The evaporation must be done very slowly. It is even advisable to collect the ether or the chloroform and evaporate it again and to add the two residues for further treatment; without this precaution negative results are frequent. Two-tenths of a cubic centimeter of 2 percent or 3 percent agar is added. The solvent is then further evaporated. The 0.2 cc of agar with the auxin is put into an agar divider [4] (fig. 1), which consists of a thin plate (*a*), the aperture of which provides, when applied to the base of the cutter, a container of 0.2-cc capacity; four small knives (made from safety razor blades) in holder are guided by a pin (*b*) on the vertical axis which slides in a groove. By lifting the holder (aided by a spring) it can be turned 90° and so allow the pin to slide down along a second groove (*d*). The razor blades make second cuts in the agar perpendicular to the first ones. Thus the agar is divided into 25 equal blocks of 8 mm^3, providing enough material for two series of 12 plants each, with practically no loss of growth substance.

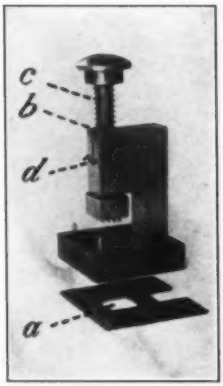

FIGURE 1.—The agar divider: *a*, Container; *b*, pin; *c*, vertical axis; *d*, groove.

In many of the tests a strongly emulsifying agent passed through the filter. In those cases the ether or chloroform layer was centrifuged and the jellylike mass which separated on top of the clear liquid and which contained some growth substances was added to the watery layer and washed out with it.

An effort was made to remove the emulsifying agents with lead salts, but they did not precipitate out. An attempt was then made to adsorb the emulsifying agents on active carbons of different quality by adding carbon to the watery solution, to the filter paper in the Büchner funnel before use, or to the filtrate. In all cases, however, the nontreated portion of the solution appeared to contain more of the growth regulators, which means that the growth substance was partially adsorbed by the carbon. Laibach and Lotz (*6*) state that if their procedure is precisely adhered to, the growth substance is adsorbed slightly or not at all on active carbon. Their table, however, shows about 50 percent adsorption for the first solution, if their fourth solution means a solution that is diluted four times. Moreover, the chemical structure (polar groups) of the true auxins shows that an adsorption on active agents is very likely to occur. The adsorption method can be applied directly to the material ground with solid carbon dioxide.

Some results obtained by the method described above are given in table 1. Extractions by other methods of the plants mentioned in table 1 gave irregular results (either small and variable or positive curvatures).

[4] This divider was constructed for the writer by P. A. de Bouter (Utrecht), and a later one by O. Westgard (Cambridge, Mass.).

TABLE 1.—*Concentration of growth substance obtained from different plant sources by different methods of extraction*

Source of extract concentrated in 25 agar blocks	Weight of material used	Method of extraction	Curvature of oat seedlings per agar block applied
	Grams		*Degrees*
Wheat seeds, soft dough	20	Solid carbon dioxide	22.9±1.5
6 immature heads of wheat plants	27	do	20.1±1.6
Basal parts of wheat plants	15	do	17.1± .2
10 tips of bryophyllum plants		do	19.3±1.3
1 tip of bryophyllum per agar block for 1 hour.		Diffusion	17.0±1.1
Tissue of potato tuber underneath buds	8	Solid carbon dioxide	19.3±1.7
Thallus of fucus		do	21.9±2.9
		Chloroform	0
		do	[1] 6.1± .9
35 oat seedlings		Solid carbon dioxide	[1] 28.8±1.9
		Solid carbon dioxide, carbon on filter	[1] 7.9±1.4
		Solid carbon dioxide, carbon in solution	[1] 2
Primary leaves of oat seedlings	2.5	Solid carbon dioxide	[1] 5.2± .5

[1] Tested simultaneously.

SUMMARY

A method for extracting growth regulators from pigmented plants is described. This method permits the demonstration of growth substances in plants that have given irregular results when extracted by other methods.

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